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Expertise

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Abstract and Keywords

The very best performers in a domain seem to possess a level of skill that is qualitatively different from that of individuals with extended experience within the same domain. This chapter addresses questions of how such exceptionally superior levels of performance are attained. While some have posited innate differences to explain elite performance, the authors review evidence that expertise is primarily the result of cognitive, anatomical, and physiological adaptations to task constraints induced by practice. Adaptations include extended working memory capacity, ability to use cues to anticipate future states of the world, and even structural and functional changes to the brain. Accumulated amount of time engaged in activities specifically focused on improving current levels of performance (deliberate practice) is the most powerful predictor of elite performance. Contrary to notions derived from the skill acquisition literature, the authors present evidence that expert performance is dynamic and adaptable, not rigid, inflexible, and automatic.

Keywords: deliberate practice, learning, expert performance, skill acquisition, adaptation

We have all probably experienced a moment in our lives in which we were awed by the exceptional performance of another. Professional juggler and Guinness World Record holder Anthony Gatto can keep eight balls flying through the air for over a minute. A chess champion can beat dozens of skilled chess players simultaneously while blindfolded. Expert mnemonist Rajan has memorized and can correctly recall the first 31,811 digits of the mathematical constant π. In a number of domains it seems that the very best performers possess a level of skill that is qualitatively different from that of highly experienced individuals within the same domain.

What is it that separates those who reach truly exceptional levels of performance from those who do not? How does expertise develop over time, and what mechanisms contribute to an expert's superior skill? What contributions do innate talent and practice make toward engendering expert performance? Several recent books, chapters, and review articles exist detailing the nature and acquisition of expert performance (e.g., Chi, 1988; Ericsson, 1996; Ericsson, 2009; Ericsson & Charness, 1994; Ericsson, Charness, Feltovich, & Hoffman, 2006; Ericsson, Nandagopal, & Roring, 2009). The purpose of this chapter is to provide a broad overview of the current state of the expertise literature. We begin by reviewing different approaches to the study of expertise. Next, we discuss characteristics of experts and expert performance, then mechanisms that contribute to an expert's skill. We also elaborate on the development of expertise over time and discuss the role that technology and simulation may play in creating exceptional performance. Finally, we conclude by highlighting unanswered questions and future directions for the understanding of expert performance.

(p. 144) Before we begin, we would like to discuss briefly what is gained from the study of experts and expert performance. As we will discuss later in this chapter, views differ regarding the relative contributions of innate talent and practice. The outcome of this research has implications for how we encourage and develop expert performance across multiple domains. If innate talent is the primary determinant of elite performance, this implies that efforts should be focused on identifying individuals with talents that match the demands of a domain and encouraging their participation and development within that domain. However, if practice is the primary determinant of elite performance, research should instead address the types of practice and training that result in exceptional performance, and efforts should be focused on providing individuals with the resources and practice opportunities necessary to attain the highest levels of performance. Furthermore, as scientists, we are often interested in not just how a system works, but what a system is *capable* of. Only the study of exceptional performance is able to provide the answer to this question. Maslow (1971) made the analogy that if we want to understand how fast a human can run, an examination of the records of Olympic gold medal winners provides a better answer than the average running times of a representative sample of individuals. Similarly, individuals interested in skill acquisition and what the mind and body are capable of must turn to the study of expert performance.

Approaches to the Study of Expertise

Defining Experts

One of the first challenges of studying expertise and its development is operationally defining what we mean by expert (Bédard & Chi, 1992; Ericsson, 2006; Ericsson & Lehmann, 1996; Ericsson & Smith, 1991). Research done in the 1970s and '80s often relied on peer nominations to identify experts. That is, professionals in a domain were asked to identify their most accomplished and skilled colleagues (Chi, 2006; Feltovich et al., 2006). However, this method often identified individuals who performed at unexceptional levels on representative tasks from their domain of expertise. Intuitive definitions of expertise that consider factors such as reputation or the number of years of experience within a domain may fail to identify individuals with exceptional performance. For example, in the domain of financial forecasting, increased length of experience does not reliably improve the quality of financial advice (Camerer & Johnson, 1991). Similarly, compared to novice therapists, highly experienced psychotherapists are no more successful in their treatment of patients (Dawes, 1994). In fact, some aspects of skilled performance, such as the ability of physicians to diagnose medical conditions based on heart and lung sounds, tend to *decrease* with increased length of professional experience (i.e., time since graduation from medical training; Ericsson, 2004). The identification of experts for study is not a trivial problem and is a critical challenge to overcome if we are to gain a scientific understanding of the nature of, and factors that contribute to, expert performance.

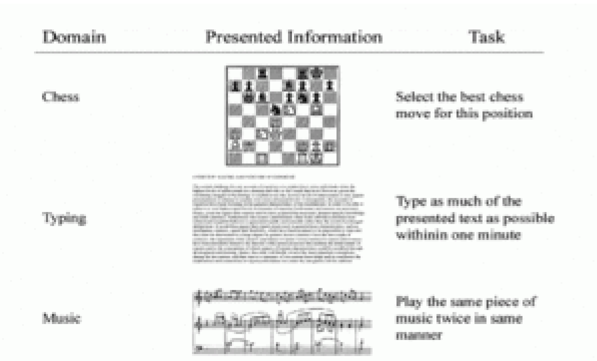

Figure 8.1 Examples of laboratory tasks that capture the consistently superior performance of domain experts in chess, typing, and music. (From "Expertise," by K. A. Ericsson and A. C. Lehmann, 1999, Encyclopedia of Creativity. Copyright by Academic Press.)

A more valid measure of an individual's skill level can come from observing his or her objective performance. For example, to classify a chess player as elite, one might consult his or her ranking based on tournament wins and losses against other rated players (Elo, 1978). Unfortunately, compared to chess, most domains lack such clearly defined tasks and performance measures. Consider the case of comparing the skill of two physicians. Physicians treat different patients with different illnesses (and even the same illness may present differently in different patients), making the comparison of skill level extremely difficult. Furthermore, neither the physicians nor we may ever know whether their diagnosis was correct or the prescribed treatment was the best. Ericsson and Smith (1991) argue that expertise should be identified based on reproducibly superior performance on representative domain-related tasks. The *expert performance approach* focuses on identifying tasks that reliably discriminate levels of performance within a domain. De Groot (1946/1978) pioneered efforts to capture expert performance in representative tasks in the domain of chess. He presented players with unfamiliar chess configurations taken from the middle of chess games and asked them to pick the next best move. He noted that that consistently superior performance on this task was indicative of a high level of chess skill. Once identified, these representative tasks can be administered under standardized conditions in the laboratory, and elements of the task can be manipulated to examine their effects. Standard methods of cognitive psychology, including the use of think-aloud protocols (Ericsson & Simon, 1993), latency, error, and eye movement analyses, can then be used to trace the source of the expert's advantage. In the example of comparing the skill of two physicians, a number of simulated patient cases based on real cases with known outcomes might be presented to both physicians to see which physician is most accurate in his or her diagnosis. Figure 8.1 depicts examples (p. 145) of representative tasks from other domains that distinguish levels of skill. As de Groot did, to assess chess skill, we might present several chess players with a series of chess positions and ask them to select the next best move. To assess typing skill, we might present typists with the same passage of text to type and record both speed and number of typing errors. In the domain of music, we might present musicians with a relatively easy piece of music and ask them to play it once. The same musicians can then asked to play the same piece again as similar to the original performance as possible. The ability to reproduce a previous performance accurately has been found to reliably differentiate levels of musical skill. Once these tasks are identified, it is possible to objectively (and relatively quickly) assess skill levels in diverse domains such as sports (Ward, Hodges, Williams, & Starkes, 2004), medicine (Ericsson, 2004), SCRABBLE (Tuffiash, Roring, & Ericsson, 2007), and music (Lehmann & Grüber, 2006). By focusing on performance instead of reputation or length of experience, the expert performance approach can identify truly exceptional individuals and the mechanisms that contribute to their skill.

The Development of Expert Performance

What allows the very best performers in a domain to attain such remarkably superior performance? Are experts innately gifted, or is their superior skill primarily the result of years of hard work and practice? These questions can be thought of as a rephrasing of the nature-nurture debate. On the nature side of the debate, a view similar to that of Sir Francis Galton (1869/1979) holds that differences in innate capacities are the limiting factor determining an individual's achievement. This view minimizes, but does not ignore, the role of practice and training. Galton proposed that although differences in innate capacities determine the maximum level of achievement an individual might attain, an individual must also possess the motivation and ability to engage in practice to reach that level of performance. Similarly, Terman (1940) viewed superior innate abilities (e.g., fluid intelligence) as a prerequisite for achievement, with environmental factors influencing whether or not individuals met their potential. Given the immense difference in performance between experts in a domain and less skilled performers, and the fact that so few individuals reach exceptional levels, explanations for exceptional performance based on innate talent are intuitively appealing. However, we will review evidence that experience rather than talent is responsible for exceptional performance.

In the skill acquisition literature, views emphasizing the importance of innate talent appear to be undermined by evidence that with practice, individual differences in performance decrease rather than increase, and general cognitive abilities become less predictive of performance after just a few hours of practice (Ackerman, 1987, 1988; Ackerman & Cianciolo, 2000). As we will discuss later, it may not always be appropriate to extrapolate from the skill acquisition literature to the domain of exceptional (p. 146) performance, but these findings are consistent with data indicating limited predictive power of general abilities in predicting the skill of chess experts (Doll & Mayr, 1987; Ericsson, Roring, &

Nandagopal, 2007; Gobet, Campitelli, & Waters, 2002). Furthermore, evidence in the domain of chess presented by de Groot (1946/1978) and Chase and Simon (1973) indicates that chess experts are relying on experience and domain knowledge accumulated over many years rather than innate ability to produce exceptional performance.

Strong evidence in favor of the acquired nature of exceptional performance comes from demonstrations of individuals with normal digit spans expanding their span to exceptional levels with training. Digit span refers to the number of digits that an individual can consistently recall without error immediately after their presentation. For most individuals this number is approximately seven digits. However, with extensive practice, dedicated individuals can expand their digit spans to more than ten times that. For example, participant SF could perfectly recall lists of 82 digits after training, and participant DD's digit span exceeded 100 items after training (Chase & Ericsson, 1982; Staszewski, 1988). A review of the evidence led Ericsson and Lehmann (1996) to propose that expertise, rather than being the result of individual differences in innate ability, represents maximal adaptations to task constraints induced by an extended period of appropriate practice. Specifically, they highlight the role of deliberate practice in producing exceptional performance.

Deliberate Practice and Exceptional Performance

As noted previously, engaging in domain-related activities for an extended period of time does not guarantee exceptional or even superior performance. Ericsson and colleagues (Ericsson et al., 1993) make a critical distinction between domain-related activities of work, play, and deliberate practice, and claim that the amount of accumulated time engaged in deliberate practice activities is the primary predictor of exceptional performance. Deliberate practice differs from other domain tasks in a number of critical ways. First, deliberate practice (often guided by a teacher or coach, but sometimes self-initiated) refers to activities with the specific aim of improving current levels of performance. These activities give the learner repeated opportunities to improve certain aspects of performance and learn from his or her mistakes. Thus feedback and monitoring of performance are critical. Compared to domain activities that fall under the category of work, deliberate practice allows for exploration and does not demand error-free performance. Deliberate practice is further characterized by activities that are effortful (and thus cannot be performed for an extended period of time without rest), not as inherently enjoyable as competing alternative activities such as play, and highly structured, which distinguishes these activities from playful interaction with peers. Ericsson and colleagues used interviews and diary data to investigate differences in daily activities between elite, good, and amateur musicians. Contrary to innate talent views, which would predict the most "gifted" musicians would require less practice to reach elite levels of performance, Ericsson and colleagues found that the very best musicians could be distinguished from good and amateur musicians by their accumulated number of hours of deliberate practice activities. In the case of violinists, by the age of 18 the most skilled violinist had accumulated 7,410 hours of deliberate practice, while good performers had accumulated 5,301, and the least skilled performers had accumulated only 3,420 hours. In addition to music, deliberate practice theory has been validated across a number of domains, including chess

(Charness, Krampe, & Mayr, 1996) and sports (Starkes et al., 1996; Ward, Hodges, Williams, & Starkes, 2007). Most recently, the role of deliberate practice in producing superior performance has been experimentally validated in the domain of college-level physics instruction (Deslauriers, Schelew, & Wieman, 2011). Students who received instruction based on the principles of deliberate practice far outperformed students who received traditional instruction, with deliberate practice producing an effect size larger than any other intervention reported in the education intervention literature.

Having identified deliberate practice as a primary determinant of exceptional performance, the important question that follows is what determines whether or not an individual engages in deliberate practice activities. Ericsson and colleagues (1993; Ericsson, 2006) highlight the issues of access to deliberate practice activities, effort constraints, and motivation to engage in deliberate practice. Without the resources to purchase or otherwise gain access to equipment and instruction necessary to engage in domain-relevant deliberate practice activities, opportunities for an individual to engage (p. 147) in such activities are obviously limited. For a child, many of these factors are not under his or her control, and thus access depends on the willingness of an individual close to the child to invest time and money to provide opportunities to engage in deliberate practice. Chronological age at which children are exposed to an activity and age at which deliberate practice activities are first engaged in is another important factor heavily under parental control as well. In terms of effort constraints, diary data collected from pianists and violinists revealed that the best performers arranged their daily schedules in a way that maximized their ability to engage in deliberate practice activities. The very best violinist studied engaged in solo practice sessions limited to between 1 and 1.5 hours per session that were distributed across the day to allow time for recovery and rest, and often napped after lunch prior to resuming training sessions in the afternoon.

The finding that current skill level is determined primarily by the accumulated amount of deliberate practice has been criticized on the grounds that the relationship between skill and deliberate practice may be an artifact induced by “dropouts.” In studies of the deliberate practice activities of experts, there could potentially be many individuals who engaged in extended periods of deliberate practice but saw no improvement in their performance and thus discontinued practice activities within a domain. If we study only expert performers who kept improving and then eventually attained exceptional levels of performance, we might incorrectly infer that everyone will improve at a similar rate with deliberate practice. Sternberg (1996) proposed that deliberate practice and talent may be confounded. Talented individuals might see larger improvements from deliberate practice activities compared to less talented individuals, motivating talented individuals to engage in deliberate practice activities more frequently. Less talented individuals, on the other hand, may get discouraged and engage in deliberate practice activities less frequently, eventually leaving the domain entirely. To address this criticism directly, de Bruin, Smits, Rikers, and Schmidt (2008) studied young elite chess players and compared players who were in the Dutch national chess training program (persisters) to those who had dropped out of the program (dropouts). In general, chess skill of dropouts lagged behind the skill of persisters. However, dropouts and persisters benefited to the same degree from deliberate practice, contrary to the criticism of Sternberg (1996). Rather than poorer performance being the result of decreased benefit from deliberate practice, the poor performance of dropouts was found to be explained by less time devoted to deliberate practice.

The 10-Year Rule

Consistent with the importance of deliberate practice even for people believed to be talented, winning performances at international competitions within competitive domains of expertise requires more than a decade of preparation. Simon and Chase (1973) argued that a minimum period of 10 years of intense preparation is required to reach exceptional (grand master) levels of chess performance. Ericsson, Krampe, and Tesch-Römer (1993) reviewed evidence that the "10-year rule" is remarkably accurate across a number of diverse domains, including long-distance running, musical composition, and scientific and creative writing. Even the most "gifted" individuals within a domain require more than 10 years of intense preparation. There is, however, no firm theoretical mechanism associated with the 10-year rule. In domains with limited competition, such as memory performance, college students were able to attain the highest recorded performance for memorizing digits in less than two years of regular training (roughly three hours per week; Chase & Ericsson, 1982; Ericsson, 1985, 2003). In highly competitive domains, such as piano performance, winners of international music competitions are likely to have studied music for over 25–30 years. In other competitive domains, such as chess, Bobby Fischer is an exception and took approximately nine years to reach an international level of grand master at the age of 15 years and six months (Krogius, 1976). Since then there have been over 20 other chess players to attain that level at younger ages. Sergey Karjakin attained the grandmaster title at the age of 12 years and six months (Wikipedia, 2009). It is generally proposed that the recent emergence of very strong chess programs and databases with chess games have allowed players to increase their chess skill much faster than was previously possible (Gobet et al., 2002). Whether it is necessary to spend seven or 10 years of intense preparation before reaching an international level of performance, such an extended prerequisite period of training, even for the most exceptional or "talented" individuals in a domain, argues against the concept of innate talent. Instead, it suggests that the key to exceptional performance is the result of increases in domain-relevant knowledge and adaptations to the demands of the task induced by practice and training.

(p. 148) Expert Performance as Adaptation

Performance can be dramatically increased with practice and training, and the attainment of elite performance is due to changes in the human body and nervous system, both of which are remarkably adaptable and plastic. If expert performance reflects maximal adaptation to a task or set of tasks within a domain, what are the various adaptations that take place to engender exceptional achievements? Research suggests that experts do not simply short-circuit neural pathways and develop automatic responses without cognitive control. Instead, experts have been found to acquire more complex cognitive mechanisms through engagement in deliberate practice. These acquired cognitive mechanisms increase the experts' working memory capacity while providing virtually immediate access to large amounts of domain-relevant knowledge, allowing experts to plan, reason, and monitor their performance and to modify aspects of their performance during deliberate practice activities. Furthermore, in domains with time pressure, the acquired cognitive mechanisms permit experts to plan, select, and execute sequences of actions in advance due to superior anticipation. By discovering subtle early cues of impending events, experts can anticipate events before they happen and thus react faster than any automatic response to the event would permit. Especially relevant to the skill of elite athletes, practice produces physiological and anatomical body changes. Finally, brain function and structure can adapt to support highly skilled performance. Each of these adaptations is discussed in turn.

Long-Term Working Memory

The ability of experts to quickly and accurately encode and access large amounts of domain-related information is inconsistent with traditional conceptions of memory derived from over a century of laboratory study. Specifically, the speed with which experts can store and access domain-related information is inconsistent with temporal constraints of long-term memory, and the ability of experts to manipulate large amounts of information online is inconsistent with capacity limitations of short-term memory. De Groot (1946/1978) found that when presented with a chess configuration from the middle of a game, expert players were able to quickly and accurately perceive good moves in the absence of extensive search. This ability implies that through many years of experience experts have acquired a vast store of knowledge that allows them to perceive opportunities and weakness in a given chess position. Simon and Chase (1973) later generalized these findings and proposed that all skilled performance relies on pattern-based retrieval mechanisms. However, pattern-based retrieval alone does not appear to explain the exceptional memory of experts. Staying within the domain of chess, chess experts can accurately mentally represent dynamically changing chess positions in the absence of a perceptually available chess board. For example, Ericsson and Oliver (described in Ericsson & Staszewski, 1989) presented a chess master with the moves of an unfamiliar game without visual access to a chessboard. After 40 moves, the chess master could quickly and almost perfectly recall the position of every chess piece. Like chess, expertise in many domains requires keeping not only a large store of domain-related knowledge but also large amounts of information in working memory during planning and reasoning about alternative actions.

Ericsson and Kintsch (1995) posit that expert performance relies on acquired mechanisms to bypass constraints of long- and short-term memory, and they highlight the importance of developing encoding strategies and retrieval structures that allow for rapid and efficient access to the contents of long-term memory. According to this view, over time experts develop the *domain-specific* mechanism of long-term working memory. In order to produce exceptional performance, the expert relies on complex retrieval structures —an organized series of retrieval cues that quickly and efficiently access relevant patterns and schemas stored in long-term memory. For example, Ericsson and Polson (1988) conducted experiments with the expert waiter JC, whose exceptional memory for food orders was traced to mnemonic encoding strategies and a retrieval structure that linked the spatial location of each customer to each category of food item (e.g., meat entrée, cooking temperature, salad, and starch). This structure allowed JC to correctly recall orders without interference from similar orders from other customers in the dinner party.

In his analyses of chess, de Groot (1946/1978) found that the chess players were not able to retrieve the *best* chess move for a chess position immediately. By having the players think aloud while they considered alternative moves, de Groot noticed that the best move was discovered only after lengthy planning and evaluation of the consequences of potential moves. The memory skill of being able to hold and manipulate chess positions in memory appears to be a critical aspect of chess skill that underlies successful move selection by planning (Ericsson et al., 2000).

(p. 149) Anticipation and Planning

A critical component of expert performance in many domains is a greater ability to anticipate future events based on acquired knowledge. For example, Abernethy and Russell (1978) had expert and novice badminton players view film of a player hitting a serve while occluding the player at different times. Compared to novices, experts were able to use visual cues present around 100 ms *before* the racquet made contact with the shuttlecock to predict where the serve would land more accurately than chance. Similarly, advanced field hockey players can more accurately predict the trajectory of the ball before an attacking player's club has made contact with it (Starkes, 1987). Among highly skilled soccer goalies, Savelsbergh, Van der Kamp, Williams, and Ward (2005) found that players who were most successful at anticipating the intended target of a penalty kicker were able to do so in part by extracting different types of visual information. Eye tracking data revealed that more highly skilled experts focused a greater amount of attention on the kicker's non-kicking leg, which has been demonstrated to provide useful information regarding the kicker's intended goal. Importantly, Savelsbergh and colleagues found that basic differences in a simple reaction time task could not explain the difference between experts who were and were not able to successfully prevent penalty goals. Instead, the differential extraction of informative visual cues allowed experts to better anticipate the future position of the ball.

In general, advanced knowledge gives the expert additional preparation time to circumvent limits in perceptual and motor processing time. Skilled typists also appear to take advantage of anticipatory processing to increase typing speed. Salthouse (1984) found that skilled typists looked further ahead in the text. Research that has filmed the fingers of expert typists has shown that the fingers often move to their designated key well in advance of the time for striking the corresponding key. When the expert typists are experimentally constrained from previewing the text, their performance is dramatically reduced toward the level of the novice typists. The expert typists' advantage is mediated by their ability to prepare keystrokes in advance of their execution. These advantages, consistent with findings in other domains of expertise, likely derive not from mere typing experience but from deliberate practice activities such as formal instruction and motivation to increase current levels of performance (Keith & Ericsson, 2007).

Physiological Adaptation

In addition to cognitive and strategic adaptations that take place as a result of deliberate practice, there is ample evidence for physiological and anatomical adaptations that contribute to the expert's exceptional performance. For example, the heart size of endurance runners is increased as a result of extended practice over time and reverts to average size at the end of their careers (Pelliccia et al., 2002). Shortly, we will review evidence of structural brain changes as a result of extended musical practice. In terms of flexibility, practice contributes to expert ballet dancers' ability to turn out their feet and baseball pitchers' ability to stretch their throwing arm back (although there is evidence that this practice may be most effective during critical periods in development before the bones and joints have been fully calcified at around age 12).

Genetic and Neurocognitive Influences

In contrast to the deliberate practice account, some have tried to explain exceptional performance in terms of unique genetic traits possessed by experts that support exceptional performance. Individual differences in genes might be expressed as the impressive anatomical and physiological differences between elite and non-elite athletes, or as differences in the function/structure of the brain allowing experts in different domains to excel. However, we present evidence that even these differences do not need to reflect innate differences, but are shaped by practice and experience.

Genetic Contributions to Exceptional Performance

In explaining exceptional performance, many have turned to individual differences in genetic endowment as a potentially important determinant of whether or not an individual is capable of achieving exceptional levels of performance (Abernethy, Farrow, & Berry, 2003; Bouchard & Lykken, 1999; Janelle & Hillman, 2003). It is clear that genes influence both physical characteristics and mental abilities. Is it appropriate to extrapolate heritability of everyday abilities to the domain of exceptional performance? Evidence reviewed thus far is strongly in favor of exceptional performance being the result of deliberate practice rather than innate individual differences. However, the notion that exceptional genotypes produce exceptional phenotypes remains popular, especially in explaining the performance of exceptional athletes. This is, no doubt, partly due to the impressive physical and physiological (p. 150) differences between elite athletes and non-athletes. Consider the differing distributions of slow- and fast-twitch muscle fibers observed between different types of elite athletes and differing abilities to metabolize oxygen (VO_2 max). At first glance these biological differences may appear strong candidates for evidence that genetic differences, at least in some domains, have a strong influence on the achievement of skilled performance. However, in a large twin study, Bouchard and colleagues (1986) found almost no genetic contribution to muscle fiber type. Additional evidence suggests that slow-twitch fiber can be converted to fast-twitch fiber with exercise (Goldspink, 2003). Finally, Bouchard and colleagues found no genetic influence on VO_2 max and noted substantial increases in VO_2 max with training (Prud'homme, Bouchard, Leblanc, Landry, & Fontaine, 1984). According to recent reviews, with the exception of height and body size, there is currently no evidence linking elite performance to individual genetic differences (Ericsson, 2007; Ericsson, Nandagopal, & Roring, 2009). Although future research may be able to establish connections between elite performance and specific genes, the current evidence suggests that physical and physiological differences between elite and non-elite athletes are primarily the result of adaptation rather than innate differences.

When considering individual differences in genetics as a basis for explaining exceptional performance, it is important to consider the fact that only a small fraction of a cell's genes are expressed, or "turned on," while the rest are turned off or repressed. Gene expression is modulated as a natural course of development and as a result of environmental conditions. The deliberate practice framework does not need to posit unique genetic attributes to those with exceptional performance, but instead explains physiological and anatomical differences between experts and non-experts as the selective expression of dormant genes that are available to all individuals. In term of physical exercise, over 100 genes are expressed and activated as a result of intense physical training (Carson, Nettleton, & Reecy, 2002).

Neurocognitive Foundations of Exceptional Performance

Is exceptional performance the product of an exceptional brain? There is a long history of scientists trying to relate individual differences in brain measures to ability (Deary & Caryl, 1997; Rushton & Ankey, 1996), Galton (1888) being among the first. In particular, Galtonian ideas appear to be influential in the detailed postmortem study of Albert Einstein's brain in an attempt to determine the source of his exceptional intellect (Diamond, Scheibel, Murphy, & Harvey, 1985; Falk, 2009; Witelson, Kigar, & Harvey, 1999). However, any attempt to explain differences in skill level as a result of *innate* individual differences in brain volume, structure, or function needs to contend with the fact that throughout the human lifespan the brain is plastic (Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Kramer & Erickson, 2007). Only minimal practice on simple laboratory tasks can induce functional reorganization of the areas responsible for task performance (Kelly & Garavan, 2004). Structural brain changes can be observed after only a few months of learning to juggle (Boyke, Driemeyer, Gaser, Büchel, & May, 2008; Draganski et al., 2004), engaging in exercise (Colcombe et al., 2006), or studying for an intense exam (Draganski et al., 2006). In the domain of music, numerous structural and functional differences can be observed between the brains of musicians and non-musicians (Bangert & Schlaug, 2006; Gaab & Schlaug, 2003; Lotze, Scheler, Tan, Braun, & Birbaumer, 2003; Pantev et al., 1998). However, these differences are almost certainly the result of differences in experience rather than innate individual differences (Bengtsson et al., 2005; Hyde et al., 2009). Interestingly, in the case of expert memorizers, Maguire and colleagues (2003) found no structural brain differences between expert memorizers and age-matched controls (nor did they differ in general cognitive abilities). Functional brain imaging revealed that during encoding, expert memorizers showed greater activity in regions important for spatial memory and navigation. This pattern of activation was consistent with the fact that most experts reported using a mnemonic method known as the method of loci. This mnemonic strategy involves participants remembering items by mentally placing objects to be remembered along an imaginary well-known route, and then mentally retracing that route during recall. Consistent with notions of long-term working memory (LTWM), participants in this study were relying on encoding schemes and retrieval structures to produce exceptional memory performance (Ericsson, 2003).

The Relationship between Skill Acquisition, Automaticity, and Expertise

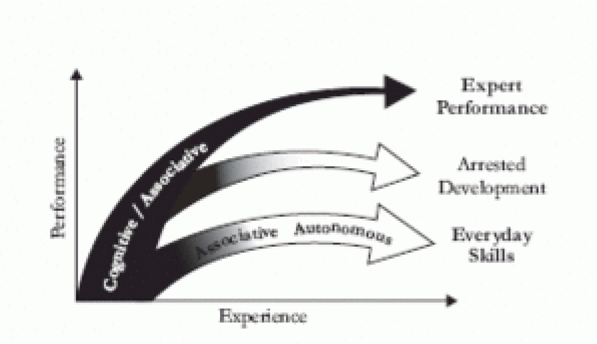

Figure 8.2 An illustration of the qualitative difference between the course of improvement of expert performance and of everyday activities. The goal for everyday activities is to reach as rapidly as possible a satisfactory level that is stable and "autonomous" (see the gray/white plateau at the bottom 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 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.)

Research on how individuals progress from novice to skilled performance has been highly influenced by the skill acquisition model proposed by Fitts and Posner (1967). This model, along with (p. 151) similar models developed by Anderson (1983) and Ackerman (1988), posit that skill acquisition progresses through a series of ordered stages with practice (see bottom arm of Figure 8.2). The initial stage, variously called the *cognitive*, *declarative*, or *controlled processing* stage, is characterized by slow, effortful, and error-prone performance as rules are learned and strategies are explored. The second stage, referred to as the *associative*, *procedural*, or *mixed controlled/automatic* stage, involves the refinement and proceduralization of declarative knowledge gained from the initial stage. Finally, after extensive practice, the *autonomous* or *automatic* stage is reached, characterized by little cognitive effort or attention being required to maintain fast and error-free performance (see Ritter, Baxter, Kim, & Srinivasmurthy, this handbook, for additional discussion of skill acquisition models).

Most models of skill acquisition consider automaticity to be the end goal of the skill acquisition process (see Moors & Houwer, 2006, for a review and discussion of automaticity). To less skilled individuals in a domain, the performance of experts often seems to share characteristics of automatic performance (fast, error-free, and seemingly effortless). However, it is important to note that most models of skill acquisition are based on performance improvements on relatively simple cognitive and psychomotor tasks over a limited time period (often measured in terms of hours). There is good reason to believe that the extrapolation of expert performance from models of skill acquisition is inappropriate. Ericsson (1998) reviewed evidence against the notion of expert performance being fully automated. Rather than performance that is rigid, expert performance is often fluid and adaptable, which is not consistent with the idea of expert performance as automated. Expert pianists, for example, can dynamically update their performance based on unexpected performance demands (Lehmann & Ericsson, 1995, 1997). Furthermore, study of chess experts suggests that part of the chess expert's advantage comes from more extensive planning and search, suggesting more complex rather than automatic performance. Additional evidence comes from the study of expert computer programmers (Koubek & Salvendy, 1991). The difference between experts and "super-experts" was found to be in the level of abstraction that super-experts represented problems rather than performance that was more automated. Finally, numerous accounts of experts displaying greater incidental memory for the details of their performance argue against automated skilled performance. We argue that in contrast to most everyday tasks, such as driving, that merely require obtaining an acceptable level of performance in a short amount of time, the development of exceptional performance does not follow the same progression from cognitive to automatic performance (see Figure 8.2). The expert, rather than working toward automaticity, through deliberate practice and adaptation retains control of the relevant aspects of performance. Deliberate practice activities that push the learner to explore strategies to continuously improve upon current levels of performance and adaptively place demands on the learner slightly beyond his or her current ability counteract the tendency to develop acceptable but unexceptional levels of performance. Through this practice, the expert acquires a more refined description of the current situation and develops refinements of his or (p. 152) her encoding methods to store this information in a retrievable form in LTWM (Ericsson & Kintsch, 1995).

Technology, Simulation, and Deliberate Practice

To adapt the principles of deliberate practice to accelerate short- and long-term skill acquisition on targeted tasks (e.g., piloting, driving, air traffic control, x-ray luggage screening, radiological screening), technology, especially in the form of simulation, may play a critical role. Take the example of an air traffic controller who may infrequently experience dangerous conflicts between aircrafts. An air traffic control simulator could give controllers repeated exposure to rare but dangerous events with immediate feedback to allow controllers to acquire an accurate and complex mental representation of this aspect of their job that might otherwise never develop or take years of on-the-job experience to construct. In the case of radiological screening, a radiologist might receive training with images from real cases with known outcomes to provide the immediate feedback often absent when real diagnoses are made. Shadrick and Lussier (2009) report how similar training can improve tactical decisions made by military commanders. Thus, technological interventions that incorporate the principles of deliberate practice—including the presentation of challenging scenarios adapted to the learner's own skill level, a focus on the practice of difficult task elements critical to successful performance, immediate and detailed performance feedback, and opportunities to redo and explore the outcome of different actions in a consequence-free environment—are likely to be the most successful way to quickly accelerate skill in everyday, safety-critical domains. The expert performance approach, as described above, can utilize similar simulated tasks to identify the strategies and cognitive structures that allow for superior performance, and these strategies and structures can then be taught to less skilled individuals through the application of deliberate practice (see Oulasvirta, Wahlström, & Ericsson, 2011, for a recent example of the expert performance approach applied to the description and understanding of skill with respect to smartphone usage).

Limits of Expertise

In addition to many studies that highlight the superior performance of experts over novices and highly skilled performers, a complete understanding of the subject of expertise must also include a description of when experts fail to demonstrate superior performance. That is, what are the limitations of expertise, and are there situations in which we might expect the superior skill of experts to break down even within their domain of expertise? Our framework for the development of expert performance proposes the acquisition of cognitive and perceptual mechanisms as well as physiological adaptations that are the result of deliberate practice. Based on this model, it is clear that we would not expect superior performance in unrelated activities or domains. In fact, many experts are highly specialized. For example, professors in physics were found to be unable to answer all questions on an introductory physics exam (Reif & Allen, 1992), and some college students were found to solve algebra problems as fast or faster than professional mathematicians (Lewis, 1981). There is another phenomenon related to the failure of experts to respond in a superior manner. With extensive experience, some "experts" seem to have attained automaticity, and they respond to situations by reacting to patterns. Some researchers have drawn on this type of evidence to describe expertise in general as brittle, inflexible, and domain-limited (e.g., Chi, 2006; Frensch & Sternberg, 1989; Lewandowsky & Thomas, 2009; Sternberg & Frensch, 1992). We argue that there are different types of expertise (see Figure 8.2). Some "experts" have, after extensive experience, automated their skills in response to familiar and routine task performance (see the middle arm of Figure 8.2). These individuals are, however, often found to achieve at a low level when given objective tests of their performance with challenging tasks. In these cases, being an expert is often defined by social recognition and/or number of years of experience rather than in terms of superior performance on representative tasks that capture the essence of expertise in that domain. In contrast, superior performers do not seem to automate relevant aspects of their performance and strive to increase their control of their performance (see the top arm in Figure 8.2). This control, or ability to monitor and adapt performance, derives directly from deliberate practice activities that focus on improvement rather than automated and stable performance and that continuously push learners outside of their comfort zone. These true expert performers are found to be able to respond flexibly when encountering new and challenging situations (for example, the expert athlete who can adjust his or her performance based on unpredictable environmental conditions such as wind). When we consider these types of expert performers, we will suggest that unexceptional (p. 153) performance in some circumstances might be a consequence of a mismatch between current task demands and the demands to which experts have spent years adapting through deliberate practice activities.

Domain-Specific Skills

Following from our understanding of expert performance as acquired adaptation to specific task constraints, it seems unreasonable to expect an expert's skill to transfer to novel tasks and unrelated domains. The learning and training literature abound with studies in which acquired skills do not fully transfer to situations that are novel, or even slightly different, compared to the context in which they were trained. Low-level perceptual learning, as well as the training of complex cognitive skills, tends to demonstrate a surprising degree of specificity (e.g., Catrambone & Holyoak, 1989; Fahle & Morgan, 1996; Fiorentini & Berardi, 1980; Pea & Kurland, 1984; Salomon & Perkins, 1987). Similarly, expertise is found to be highly domain-specific. The exceptional memory that chess experts demonstrate in recalling the position of chess pieces on a board is greatly reduced when chess pieces are placed on the board randomly compared to when they are arranged as they might appear in a game (but see Gobet & Simon, 1996a,b, for evidence of expert superiority for random positions and Ericsson et al., 2000, for how the acquired skill might account for that superiority). Rajan's exceptional memory skills are reduced to unexceptional levels when presented with non-alphanumeric stimuli that prevent him from relying on encoding strategies (Ericsson, Delaney, Weaver, & Mahadevan, 2004). In the field of chemistry, experts used similar solutions to novices and performed as poorly as novices on a political science problem compared to expert political scientists (Voss, Greene, Post, & Penner, 1983). In general, it appears that expertise in one domain does not appear to benefit the development of expertise in another, as evidenced by the few individuals who demonstrate expert performance across multiple domains (Ericsson & Lehmann, 1996) and those rare individuals who do have extensive practice histories in both domains. While in some sense poor transfer to tasks that appear similar to tasks within the expert's domain may be surprising, it is perfectly consistent with the framework of exceptional performance we have discussed thus far. We have conceptualized expertise as maximal adaptation to the demands of tasks within a domain through deliberate practice. This adaptation includes not only mechanisms to deal with the demands of previously encountered domain-related tasks but also mental representations that permit reasoning about unfamiliar situations drawing on the vast knowledge base developed over many years. When highly experienced individuals who lack these relevant mental representations and associated knowledge are confronted with unfamiliar situations, it is not surprising that an expert will perform poorly.

Inflexibility

It has been claimed that experts can demonstrate performance that is inflexible. For example, skilled chess players can be more susceptible to the Einstellung effect. When presented with a chess problem, chess experts can often be lured into engaging in nonoptimal but familiar solutions instead of novel, more efficient solutions (Saariluoma, 1990). However, in a recent study, Bilalic, McLeod, and Gobet (2008) found that the best chess players did find optimal solutions, suggesting that suboptimal move selection is characteristic of chess players of intermediate rather than very high levels of expert skill. Similar effects of inflexibility have been demonstrated in the domain of tax law (Marchant, Robinson, Anderson, & Schadewald, 1991). Compared to novices, highly experienced tax practitioners were more likely to rely on previous knowledge than newly acquired knowledge about a similar case. However, inflexibility was an exception rather than the rule (i.e., observed in anomalous cases in which a general tax principle did not apply). As reviewed previously, automatic and inflexible performance does not appear to be consistent with expert performance.

Expediency

Lewandowsky and Kirsner (2000) present another potential limitation of expertise: expediency. In predicting the spread of wildfires, experienced wildfire commanders relied almost solely on information about wind direction and ignored the slope of the terrain, even though both determine the direction of the spread of wildfires. In other words, commanders relied on a quick and efficient predictor of wildfire direction that was correct most of the time instead of considering all available cues. While this is an interesting property of the highly experienced individuals studied, it remains unclear at this point how expediency relates to individuals with reproducibly superior performance. Heuristics may produce fast and accurate performance most of the time, but true expert performers should also (p. 154) demonstrate superior performance in exceptional cases.

Conclusion

Here we have presented evidence that expertise and exceptional performance, rather than arising from innate talent or genetic endowment, are the result of mental and physical adaptations acquired over an extended period of time to maximize performance of a specific task or set of tasks. Methodologically, expertise and the mechanisms that support it can be studied in the laboratory with domain-relevant representative tasks on which experts demonstrate reproducibly superior performance. Although performance on everyday tasks is often correlated with scores on tests of general abilities that have shown significant heritabilities, we argue that similar evidence is not available for expert and exceptional performance. Instead, current evidence suggests that access, ability, and willingness to engage in deliberate practice activities are the primary determinants of exceptional performance.

Commentators on research on expertise frequently discuss the limits of expert skill and the cost of expertise. Instances in which experts fail to produce exceptional performance are interesting and contribute to our understanding of the mechanisms that contribute to their skill. However, generalizing from the skill acquisition literature to the domain of expert performance tends to mischaracterize expert performance as inflexible, outside of conscious control, and requiring little attention. On the contrary, expert performance is more adaptable to changing demands, experts demonstrate greater incidental memory for the details of their performance, and expert performance is often characterized by more planning.

Although we conclude that it is inappropriate to extrapolate from the skill acquisition literature to levels of expert performance, there are intriguing parallels between the two areas of research that may be worth further exploration (see Ritter, Baxter, Kim, & Srinivasmurthy, this handbook, for additional discussion of learning and retention). The idea of deliberate practice is highly consistent with training methods described as variable priority training. Variable priority training involves asking participants to practice a complex task while alternately focusing their attention on improving specific subcomponents of the task at different times while being provided with specific performance feedback (Gopher, 2007). Compared to other training methods, variable priority training has been demonstrated to accelerate learning, maximize skill mastery, and engender broader transfer of training to novel tasks (Fabiani, Buckley, Gratton, Donchin, & Logie, 1989; Gopher, Weil, & Siegel, 1989; Kramer, Larish, & Strayer, 1995). Furthermore, consistent with the importance of rest and recovery time in the deliberate practice framework, simple skill acquisition also benefits from spaced versus massed practice (e.g., Donovan & Radosevich, 1999; Underwood, 1961; Shebilske, Goettl, Corrington, & Day, 1999). Whether principles of short-term skill acquisition can be successfully extended to account for some aspects of the development of exceptional performance raises interesting theoretical issues and suggests fruitful topics of future empirical research. Initial evidence suggests that deliberate practice principles can be successfully applied to shorter-term skill acquisition (e.g., Deslauriers, Schelew, & Wieman, 2011; Shadrick & Lussier, 2009).

Although innate differences in brain structure and function have not been successfully linked to exceptional performance, neuroimaging still has the potential to reveal much about how expertise is instantiated in the brain. Many domains in which individuals display exceptional performance do not easily lend themselves to neuroimaging techniques due to their complexity. However, the expert performance approach may be able to identify domain-relevant tasks that distinguish different levels of performance that are more suitable for various brain-imaging techniques such as ERP and fMRI.

Finally, currently deliberate practice rather than individual differences in genetic endowment appear to provide the best explanation for the development of exceptional performance. On the other hand, genotypes influence phenotypes, and the methods for examining individual differences in genetic makeup are improving. There is no evidence that rules out the effects of genetic components on the development of exceptional performance. Consequently, future research may well find particular genes that only some individuals possess as part of their DNA that differentially affect the development of particular skills and expert performance in various domains of expertise. This could include genetic determinants of individual differences in motivation and ability to engage in deliberate practice. Regardless of whether some individuals benefit from innate talent provided by an exceptional genome, we still need to understand the detailed mechanisms of how deliberate practice activities cause both innately talented and other individuals to improve their initial levels of performance.

(p. 155) Future Directions

- *Identifying, measuring, and capturing reproducibly superior performance*. There are a number of different types of expertise and professional performance where individuals with reproducibly superior performance have not as yet been identified. Until such superior performance can be successfully measured and reproduced in a given domain, it would be meaningless to attempt to describe any of its mediating mechanisms and how they were acquired. In many of these cases nobody has even tried to measure it, but in others efforts have actually failed (cf. decision making of experts).
- *The structure of acquired mechanisms mediating expert performance*. One major issue is describing the nature and extent of individual differences in mechanisms mediating a given level of performance. It should be possible to describe the structure of individual experts' mechanisms, in a manner similar to how individual differences in the structure of memory skills have been described (Chase & Ericsson, 1981, 1982; Ericsson et al., 2004; Ericsson & Polson, 1988; Hu et al., 2009). These efforts are necessary to describe individual differences in skill and their mediating mechanisms.
- *Description of the development and acquisition of expert performance*. We are only beginning to be able to describe the type of deliberate practice that would be appropriate for an individual who wants to improve his or her performance beyond the current level. It will be important to characterize the type of training that would be optimal for beginners and for children, adolescents, and adults starting to acquire a given skill. Will there be large differences depending on the age of the learner? To what extent will there be developmental windows where certain types of acquired adaptations will be more easily acquired? Is it possible to acquire some basic characteristics during development that facilitate acquisition of a wide range of other types of skills during adolescence and adulthood—in the search for general adaptations?

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