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EXPERT AND EXCEPTIONAL PERFORMANCE: Evidence of Maximal Adaptation to Task Constraints

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ABSTRACT

Expert and exceptional performance are shown to be mediated by cognitive and perceptual-motor skills and by domain-specific physiological and anatomical adaptations. The highest levels of human performance in different domains can only be attained after around ten years of extended, daily amounts of deliberate practice activities. Laboratory analyses of expert performance in many domains such as chess, medicine, auditing, computer programming, bridge, physics, sports, typing, juggling, dance, and music reveal maximal adaptations of experts to domain-specific constraints. For example, acquired anticipatory skills circumvent general limits on reaction time, and distinctive memory skills allow a domain-specific expansion of working memory capacity to support planning, reasoning, and evaluation. Many of the mechanisms of superior expert performance serve the dual purpose of mediating experts' current performance and of allowing continued improvement of this performance in response to informative feedback during practice activities.

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INTRODUCTION

Human behavior is enormously adaptive to environmental demands. In psychology, the most important changes in behavior are attributed to learning, as are changes in cognition, brain function, and many other modifications of the human body. Some adaptive changes, such as increase in muscle volume in response to exercise, are commonly observed and are accepted as a natural result of training activities. However, recent research in developmental biology shows that physical adaptation is more far-reaching than is commonly believed. For example, the shape of the eye is affected by an individual's visual activity; the increased incidence of near-sightedness in Western cultures appears to be an adaptive reaction to watching TV, reading, and other activities requiring sustained focus on nearby objects (Wallman 1994).

The adaptability of human behavior presents a challenge to scientists who seek to identify invariant characteristics and to propose general laws that describe all forms of behavior. We suggest that the most promising approach to finding invariants and exceptions to them is to study cases of maximal adaptation and learning, such as the behavior of experts. Expert performers devote most of their lives to attaining the highest levels of performance in a highly constrained activity (Ericsson & Charness 1994, Ericsson et al 1993). They often start training at very young ages, and the duration and intensity of their sustained training far exceed the range for other activities pursued by individuals in the normal population.

VIEWS OF EXPERT PERFORMANCE

It is generally assumed that outstanding human achievements reflect some varying balance between training and experience (nurture) on one hand and innate differences in capacities and talents (nature) on the other. One view, typically associated with Galton's work (1869/1979), holds that individual differences reflect innate basic capacities that cannot be modified by training and practice. The second and more recent view, typically associated with de Groot (1946/1978) and with Chase & Simon (1973), is that experts' knowledge and task-specific reactions must have been acquired through experience. These two views define mutually exclusive domains corresponding roughly to the popular distinction between hardware and software in computer-based metaphors for human information processing.

In the view of expert performance as talent, instruction and practice are necessary but not sufficient to attain expert levels of performance. Performance increases monotonically as a function of practice toward an asymptote representing a fixed upper bound on performance. Contemporary researchers who hold this view generally assume that training can affect some of the components mediating performance but not others, and that stable, genetically determined factors constrain the ultimate level of performance. Consequently, empirical research has focused on identifying and measuring talent relevant to particular types of activity. A practical extension of this view is that, by testing individuals at a young age, one can select the most talented children and provide them with the resources for the best training. Later in this chapter we briefly review the evidence, or rather the lack of firm evidence, for the talent-based view of expert performance.

At the time de Groot (1946/1978) started his research on chess expertise, the prevailing view was that chess experts achieved their superior performance by greater than normal intellectual capacity for extensive search of alternative chess moves. However, de Groot (1946/1978) found that world-class chess players accessed the best chess moves during their initial perception of the chess position, rather than after an extensive search. This finding implied pattern-based retrieval from memory and is fundamental to Chase & Simon's (1973) and Simon & Chase's (1973) theory of expertise. Chase & Simon showed that pattern-based retrieval can account for superior selection of chess moves and exceptional memory for chess positions without violating general limits to human information processing (Newell & Simon 1972), including the limited capacity of short-term memory.

Chase & Simon (1973) proposed that the attainment by experts of many other forms of expertise, in fact "any skilled activity (e.g. football, music)" (p. 279), was the result of acquiring, during many years of experience in their domain, vast amounts of knowledge and the ability to perform pattern-based retrieval. This assertion was borne out by subsequent research on solving textbook problems in physics (Larkin et al 1980, Simon & Simon 1978). Novices, who possessed all the necessary knowledge, struggled with physics problems and retrieved formulas and computed results by working backward from the question, whereas physics experts retrieved a solution plan as part of their normal comprehension of problems. Chi et al (1982) showed that physics experts not only had more knowledge than novices but also organized it better. Experts could therefore represent physics problems in terms of the relevant theoretical principles, whereas novices' representations were based on salient surface elements. Voss et al (1983) showed that expert reasoning is specific to a domain. Their subjects, experts in domains such as chemistry and social science, lacked the special knowledge and strategies to successfully analyze a problem in political science. More recently, researchers have designed methods to elicit experts' knowledge (Cooke 1994; Hoffman 1987, 1995) and to describe its structure and organization in specific domains (Hoffman 1992, Olson & Biolsi 1991). Glaser & Chi (1988) and, more recently, Bédard & Chi (1992) and McPherson (1993a) have reviewed this knowledge-based approach to expertise. This view is consistent with theories of skill acquisition (Anderson 1983, 1993; Fitts & Posner 1967), in which knowledge is first acquired and then organized into appropriate actions that, with further practice, individuals can access automatically through pattern-based retrieval. For reviews of the important progress in the laboratory study of skill acquisition, see Proctor & Dutta (1995) and VanLehn (1989, 1996).

Following a related view, some investigators have equated expertise with the amount and complexity of knowledge gained through extensive experience of activities in a domain.[1] However, recent studies have shown that individuals with expertise defined in this manner do not necessarily exhibit performance that is superior on relevant tasks to the performance of less-experienced individuals. The dissociation between level of expertise (based on the amount of experience) and performance has been most clearly demonstrated in many types of expert decision making and judgment (Camerer & Johnson 1991). In their review, Shanteau & Stewart (1992) found that the validity and reliability of expert judgments were typically low and unrelated to the amount of experience. Furthermore, statistical regression models that combine a small number of cues usually available to experts nearly always outperform (or at least equal) expert judgment involving prediction (Dawes et al 1989). Human expert judgments are superior to such models primarily in well-defined domains with developed theories supporting reasoning, such as medicine and bridge. Several efforts have been made to distinguish additional characteristics of task domains in which expert judges display superior performance (Bolger & Wright 1992, Shanteau 1992). The availability of rapid feedback appears to be a critical factor for improvement of decision accuracy. For example, nurses screening emergency calls for medical help improve their response accuracy as a function of years of experience (Leprohon & Patel 1995).

The amount of auditors' general experience in their domain is poorly related to the accuracy of their performance (Bonner & Pennington 1991), and in this domain consensus among experts for important evaluations decreases with experience (Bédard 1991). Similarly, extensive experience in interactions with

[1] Amount of overall experience in a domain should be distinguished from the amount of time spent on focused activities designed to improve performance (deliberate practice), because the latter has been found to be closely related to the attained level of performance (Ericsson et al 1993).

a computer system does not automatically lead to knowledge and proficiency (Rosson 1985, see Ashworth 1992 for a review). In many domains, such as mathematics (Lewis 1981), computer programming (Doane et al 1990), and physics (Reif & Allen 1992), some of the experts failed to demonstrate superior performance on representative activities. Part of the problem is that most experts are highly specialized, and task-specific experience is a better, but still modest, predictor of performance (Bonner & Pennington 1991).

These findings raise troubling issues about the relation of experience-based expertise and consistently superior performance. We agree with other investigators (e.g. Edwards 1992, Sternberg & Frensch 1992) who assert that empirical investigations should focus on reproducible superior performance, because the analysis of its mediating mechanisms is likely to provide evidence for adaptations to task constraints.

SCOPE OF EXPERT PERFORMANCE

One of the marks of expert performers is that they can display their superior performance reliably upon demand. To achieve this control, expert performers need to master all relevant factors—including motivation. Hence, expert performers should be able to reproduce their superior performance on representative tasks presented under controlled laboratory conditions, and their performance can therefore be subject to scientific analysis.

Following Ericsson & Smith (1991a), we define expert performance as consistently superior performance on a specified set of representative tasks for a domain. The virtue of defining expert performance in this restricted sense is that the definition both meets all the requirements for carrying out laboratory studies of performance and comes close to meeting those for evaluating performance in many domains. At the same time it excludes those domains where investigators have been unable to supply a valid measure with associated demonstrations of superior performance.

In most domains, methods have evolved to reliably measure individuals' performance under standardized conditions, which make experts easy to identify. Their consistently superior performance has then been successfully reproduced and experimentally studied in the laboratory with representative tasks (see Ericsson & Charness 1994 for a review). At least in the traditional domains of expert performance, intriguing generalities have been discovered.

Age and Peak Performance

The age at which experts typically attain their highest levels of performance is closely related to their domain of expertise (Lehman 1953). In vigorous sports the age distributions for peak performance are remarkably narrow. They center in the twenties and exhibit systematic differences across different sports and activities within a given sport (Schulz & Curnow 1988, Schulz et al 1994). The highest achievements in fine motor skills and even in predominantly cognitive activities, such as chess (Elo 1965), occur most frequently for experts in their thirties (Lehman 1953). In the arts and sciences there is a close relation between the time of the most creative and unique achievements and the time of highest productivity, that is, consistent (reproducible) generation of quality products (Simonton 1988); peak ages for the most creative achievements most frequently fall in the thirties and forties. Peak ages systematically differ even across the primarily cognitive domains (Simonton 1988) and even within domains—for example, between postal and tournament chess (Charness & Bosman 1990).

The 10-Year Rule of Necessary Preparation

That experts in most domains attain their highest level of performance a decade or more after physical maturation points to the importance of extensive preparation. Simon & Chase (1973) made an even more direct claim about the necessity for intense preparation. They found that it takes chess players around ten years of preparation to attain an international level of chess skill. Even the chess prodigy Bobby Fisher needed a preparation period of nine years (Ericsson et al 1993). Simon & Chase also suggested that similar preparation is required in other domains, and subsequent studies (Bloom 1985, Hayes 1981) indicate that the 10-year rule can be generalized to several different domains, including vigorous sports. According to this rule, not even the most "talented" individuals can attain international performance without approximately 10 years of preparation; the vast majority of international-level performers have spent considerably longer.

More generally, the mere number of years of experience with relevant activities in a domain is typically only weakly related to performance (Ericsson et al 1993). Even more refined measures, such as the number of hours in chess competitions (Charness et al 1995) and the number of baseball games in the major leagues (Schulz et al 1994) only weakly predict individual differences in performance among skilled performers.

The Role of Deliberate Practice

An important reason for the weak relation between experience and performance is that many of our most common activities, such as work and competitions, play and leisure, afford few opportunities for effective learning and improvement of skill. Drawing on research on learning and skill acquisition and on the educational practices in traditional domains such as music and sports, Ericsson et al (1993) used the term deliberate practice for the individualized training activities especially designed by a coach or teacher to improve specific aspects of an individual's performance through repetition and successive refinement. To receive maximal benefit from feedback, individuals have to monitor their training with full concentration, which is effortful and limits the duration of daily training. Ericsson et al argued that the amount of deliberate practice should be closely related to the level of acquired performance.

In fact, individual differences in the amount of deliberate practice, determined from diaries and retrospective estimates, were shown to be related to the level of performance attained by expert musicians and athletes (see Ericsson et al 1993 for a review). Furthermore, the age at which elite performers started deliberate practice was systematically younger than that of less accomplished performers. An analysis of these performers' daily patterns of practice and rest indicated that their maximal amount of fully concentrated training that they could sustain every day for years without leading to exhaustion and burn-out was around four hours a day.

In many domains, knowledge of effective training procedures has accumulated over a long time, and qualified—often professional—teachers draw on this knowledge to design deliberate practice regimens for individual students. In domains such as chess, for which there is no organized system of formal training, Ericsson et al (1993) found practice activities that have the characteristics of deliberate practice and were thereby able to extend their research framework to these domains. From informal interviews with elite chess players, they learned that these players created optimal learning situations by studying published chess games for several hours every day and attempting to predict—one by one—the moves chosen by chess masters. A subsequent study confirmed that ratings of chess skill were closely related to the total amount of time chess players have devoted to the study of chess (Charness et al 1995).

Expert Performance and Talent

The belief that most anatomical and physiological characteristics are unmodifiable and thus reflect innate talent is not valid for expert performance acquired through at least a decade of intense practice. Ericsson et al (1993) and Ericsson (1990) reviewed evidence showing that observed changes in response to long-term intense training, such as the size of hearts, the number of capillaries supplying blood to affected muscles, and the metabolic properties of critical muscles (conversion of fast-twitch and slow-twitch muscles), revert to values in the normal range when athletes' training is decreased. Once many of these changes have occurred, however, they can apparently be maintained with regular training at lower frequency and duration (Shephard 1994).

There is evidence suggesting that practice at young ages when the body is developing may be necessary for certain adaptations to take place. Early training appears necessary for classical ballet students to change their joints and give them maximal turnout at the hip (Miller et al 1984). Contrary to common belief, these changes do not reflect an increased range of flexibility. The range of these dancers' movements in the opposite direction is reliably decreased compared to that of control subjects (Hamilton et al 1992). Similar results have been found for musicians (Wagner 1988). More generally, vigorous physical activity stimulates the growth of bones and joints (Bailey & McCulloch 1990, Martin & McCulloch 1987, Sammarco & Miller 1982); these adaptations, however, are restricted to those limbs that are involved in this activity. This specificity is particularly salient in unilateral activities, such as baseball pitching (King et al 1969) and racquet sports (Jones et al 1977). Many of the anatomical and physiological differences between individuals in the general population and elite athletes, dancers, and musicians can be accounted for by intense training that exposes parts of these performers' bodies to specific stimulation well outside the normal range encountered during everyday life.

Recent research has refuted earlier claims that several perceptual, motor, and cognitive capacities cannot be obtained through training and practice. With appropriate instruction (Biederman & Shiffrar 1987), college students can acquire the mysterious ability to identify the sex of chicks (Gibson 1969). World-class typists (Book 1924) and expert pianists (Keele & Ivry 1987) appear to acquire the ability to tap their fingers at a superior rate because this skill, at least in the case of pianists, is correlated with the amount of deliberate practice (Ericsson et al 1993) and does not generalize to the rate of tapping feet (Keele & Ivry 1987). The exceptional abilities of children and autistic savants can be explained by the acquisition of skills without assuming special talent at the outset (Howe 1990, Ericsson & Faivre 1988). Finally, the ability of some musicians to correctly name pitches (absolute pitch) is related to early exposure to music and the start of musical training. In their review, Takeuchi & Hulse (1993) argued that any child can acquire perfect pitch until the age of around six. Early exposure to pitch recognition activities appears sufficient to account for the development of differences in brain structure associated with perfect pitch (Schlaug et al 1995). In animals, differential morphological changes of the brain result from different types of extended practice activities (Black et al 1990).

Numerous studies of basic perceptual abilities and reaction time have not found any systematic superiority of elite athletes over control subjects (see Abernethy 1987a and Starkes & Deakin 1984 for reviews). Similarly, experts in visual medical diagnosis show no consistent advantage in basic perceptual capacities over control subjects (Norman et al 1992b). Furthermore, IQ is either unrelated or weakly related to performance among experts in chess (Doll & Mayr 1987) and music (Shuter-Dyson & Gabriel 1981); factors reflecting motivation and parental support are much better predictors of improvement (Schneider et al 1993). This is consistent with a general finding that the correlation between IQ and performance in a domain decreases over time, and after more than five years of professional experience the correlation is no longer reliable, even after appropriate statistical correction for restrictions of range (Hulin et al 1990).

Reviews of adult expert performance show that individual differences in basic capacities and abilities are surprisingly poor predictors of performance (Ericsson et al 1993, Regnier et al 1994). These negative findings, together with the strong evidence for adaptive changes through extended practice, suggest that the influence of innate, domain-specific basic capacities (talent) on expert performance is small, possibly even negligible. We believe that the motivational factors that predispose children and adults to engage in deliberate practice are more likely to predict individual differences in levels of attained expert performance.

THE STUDY OF EXPERT PERFORMANCE

Expert performance acquired over many thousands of hours of deliberate practice is unlikely to improve in response to a few hours of laboratory testing, provided that the laboratory settings faithfully reflect the tasks and constraints of the natural conditions (Ericsson & Smith 1991a). The major challenge to investigators is therefore to develop a collection of standardized laboratory tasks that capture the essential aspects of a particular type of expert performance.

Capturing the Phenomena of Expert Performance in the Laboratory

For some types of expert performance such as typing, juggling, and exceptional memory, the conditions under which these acts are performed are so standardized that they are easily reproduced in the laboratory. For other types, it is very difficult to reproduce the perceptual conditions or even to design a collection of standardized tasks that captures the essential characteristics of superior performance in a domain. The methodology for assessing specific types of expert performance in the laboratory is still emerging, and we report on investigators' solutions to these problems in different domains.

In sports, investigators discovered long ago that performance on tasks, where sports situations were represented abstractly, did not differ between various levels of athletes (see Tenenbaum & Bar-Eli 1993 for a review). Perhaps as a consequence, some of the most careful re-creations of actually occurring situations are found in sports, e.g. Helson & Pauwels (1993).

Recent advances in video and computer technology offer exciting possibilities for very high fidelity of reproduction. However, to capitalize on the control offered by laboratory studies, we recommend that investigators strive for the minimum of complexity necessary to successfully reproduce the relevant expert performance.

Analysis of Captured Expert Performance

It is important to distinguish tasks that capture the essence of expertise in a domain from other tasks in which the experts may also excel. For example, chess experts' ability to consistently select superior chess moves for arbitrary positions from chess games is a definitive feature of chess skill, whereas exceptional memory for chess positions is not.

In this first section we review only studies of expert performance captured with standardized tasks under normal or experimentally varied conditions. The cognitive processes that mediate superior performance have been examined using more traditional process data, such as reaction time, eye fixations, verbal reports (Ericsson & Simon 1993), or incidental recall. In the subsequent section we review research on a broader range of tasks that examined selected aspects of experts' performance.

EXPERT PERFORMANCE IN TRADITIONAL DOMAINS *Chess* The study of expert performance originated with the study of chess experts, and chess has remained the major domain for testing theories of expertise. To capture expert performance in chess, de Groot (1946/1978) identified chess positions for which he had extensively studied the consequences of various moves. He presented chess players with one of these chess positions and asked them to think aloud while selecting the best move. Comparing the think-aloud protocols of world-class players to those of good players in local chess clubs, de Groot found that both types of players engaged in extensive planning and search, but that the depth and amount of search did not differ. However, world-class players selected better moves than did the club players, who often failed to consider the best move.

From the findings that the world-class players frequently accessed the best move as one of their first possibilities in their original representation of the chess position, de Groot (1946/1978, also Chase & Simon 1973) inferred that chess masters do not generate chess moves by search but rather by cued recall from memory. Calderwood et al (1988) and Gobet & Simon (1995a) supported that claim and found that the quality of selected chess moves remained high when the time available for the search was drastically reduced.

Many studies have replicated superior move selection as a function of chess skill and have analyzed the mediating processes. For example, Charness (1981a) and Gruber (1991) found that the depth of search increased with chess skill up to the level of chess experts, although further increases in depth of search beyond that skill level have not been observed (Charness 1989, de Groot 1946/1978). Holding (1989) obtained more direct experimental evidence for improved move selection by search. He found that the amount of search and the quality of selected moves decreased when chess players had to perform a demanding secondary task while selecting a move. Holding & Reynolds (1982) found that expert chess players discovered superior moves for chess positions even when recognition-based access to moves from memory was prevented.

Both recognition-based retrieval and search appear to be important to selecting the best move (Saariluoma 1990, 1992). When confronted with a chess position, chess players retrieved potential moves on the basis of their representation of the position, where better representations allowed access to moves that were more in line with associated long-term strategic goals. The search primarily helped to evaluate alternative approaches and eliminate possible oversights and errors (Saariluoma 1992). However, even the world-class chess players studied by de Groot (1946/1978) would occasionally discover superior moves as the result of their search.

In sum, expert selection of moves in chess is mediated by retrieval of appropriate goals and moves from memory, and—if time permits—by systematic higher-level search and evaluation. Experts also exhibit superior incidental memory[2] for the examined positions (Charness 1981b, Lane & Robertson 1979).

Medicine Along with chess, medical reasoning and diagnosis are among the traditional domains of research on expertise (see Elstein et al 1990 for a review). Typically, subjects have been instructed to think aloud or comment as they inspect information describing a case. Although medical experts receive extensive training in medical school, during internship, and within their specialty, it has been surprisingly difficult to demonstrate superior diagnostic performance for typical cases beyond the performance medical experts attained during their first year of residency (Norman et al 1992b, Schmidt et al 1990). Small but reliable differences are seen (Winkler & Poses 1993), and more recently larger differences in diagnostic accuracy as a function of medical expertise have been observed in tests of diagnostic performance for difficult cases (Norman et al 1994, Patel & Groen 1991). Recent theoretical reviews (Patel et al 1994, Schmidt et al 1990) show a consistent picture of the development of expert diagnostic performance from medical students with a lot of general medical knowledge to medical experts with structured clinical knowledge that supports the generation of accurate diagnoses.

[2] A discussion of effects of aging on expert performance is outside the scope of our review and interested readers are directed to recent reviews by Ericsson & Charness (1994) and Krampe (1994).

In one of the pioneering studies of medical diagnosis, Feltovich and coworkers (1984) contrasted medical students' difficulties in retrieving their relevant knowledge with the medical experts' effortless access to their highly organized knowledge of diagnostic alternatives. More recently, Boshuizen & Schmidt (1992) showed that medical experts have acquired higher-order concepts relating clinical information to diagnostic alternatives that replace the extensive biomedical reasoning of medical students and interns. Lemieux & Bordage (1992) found that superior diagnostic performance was associated with higher-level and more refined inferences generated from the presented clinical information. Patel et al (1994) found evidence for a working memory representation based on facts that summarize clinical findings and that allowed flexible reasoning about diagnostic alternatives. This representation enabled experts to recover from initially incorrect hypotheses, evaluate diagnostic alternatives, and construct an explanation of all relevant clinical findings.

In sum, expert performance in medical diagnosis is primarily found for difficult cases that compel experts to reason extensively about diagnostic alternatives. Consistent with chess experts, medical experts have very good incidental memory for the relevant information in their domain (Hassebrock et al 1993), and the amount of information recalled typically increases with expertise (Norman et al 1989a).

Bridge The critical task that can be isolated for an individual bridge player is playing a given hand in such a manner that the contracted number of tricks are won. With information from bidding and a given bridge hand, experts are very accurate in estimating the probability of making a particular number of tricks (the contract); amateur bridge players are more biased and show systematic overconfidence (Keren 1987). Think-aloud studies of bridge players planning to play a given bridge hand show that experts perceive problems and constraints better and plan more extensively than less skilled players (Charness 1989). After a game, incidental memory for the original bridge hands increases with bridge skill (Engle & Bukstel 1978).

Auditing Only a small number of auditing tasks such as prediction of bankruptcy, detection of fraud, and detection of accounting mistakes, have known correct solutions (Bédard & Chi 1993). Although auditors can reliably predict bankruptcy for collections of documented cases (see Whittred & Zimmer 1985 for a review), their bankruptcy judgments for contemporary firms are problematic because these judgments are public and may themselves influence the probability of bankruptcy (Bonner & Pennington 1991). Investigators have been more successful in analyzing think-aloud protocols of the fraud detection process (Johnson et al 1991, 1992) and of the identification of deliberately seeded mistakes (Bedard & Biggs 1991a,b). Two generalizable conclusions have emerged. The amount of experience auditors have with general accounting does not predict accuracy, whereas the amount of experience with particular types of firms does, especially experience with medical firms, where the rate of fraud is comparatively high. In accord with the findings from expert medical diagnosis, the primary difficulty in successful identification of fraud is not so much the detection of isolated inconsistencies but the generation of an integrated explanation of patterns of deviations.

OTHER DOMAINS In many domains of expertise, it is difficult to identify representative tasks with well-defined correct responses because the products generated in these domains—computer programs, research designs, and written papers—are complex. Most of the recent research on experts has been conducted in the domain of computer programming with highly experienced professionals as subjects (Adelson & Soloway 1985, Jeffries et al 1981). Experts and nonexperts have been given the same program specifications, and their subsequent design processes have been monitored with think-aloud protocols. In these studies, expert programmers, unlike novices, were found to generate an initial higher-level representation of their design (mental model) and to modify it until it met all the requirements. Only later did they proceed to a detailed design of its components. When the presented task was familiar to the experts, they often rapidly retrieved or constructed an accurate mental model (Adelson & Soloway 1985, Jeffries et al 1981), but when the task was not familiar, experts spent considerable effort generating a mental model that satisfied all the relevant constraints (Adelson & Soloway 1985, Guindon 1990). When Koubek & Salvendy (1991) monitored problem solving by expert and "super-expert" programmers on a program modification task, they found evidence not for automatization of the super-experts' performance but rather for reliance on a more general and abstract representation of the computer program than the regular experts had.

Similarly, research contrasting expert and nonexpert writers shows that experts expend more effort on planning and consider additional constraints regarding organization, structure, and intended readers than less skilled writers do (Bryson et al 1991, Flower & Hayes 1980, Kellogg 1994). Consistent with results for routine problem solving, Schraagen (1993) found that highly experienced scientists could easily generate research designs for familiar problems in their own area of research but not for problems in an unfamiliar area.

Recent research on expertise in physics (see Anzai 1991 for a review) has focused on the representation of concepts and on the externalized representation of physics problems as diagrams (Larkin & Simon 1987). In their study of novices and physics professors, Reif & Allen (1992) collected think-aloud protocols on reasoning about acceleration in many well-defined tasks. They found that the acquisition of an integrated, accurate representation of theoretical concepts is not an inevitable consequence of extended experience; even some of the professors "exhibit marked deficiencies in concept interpretation" (p. 1).

Remarkably accurate and complex reasoning has been observed in some individuals who regularly bet on horse races (Ceci & Liker 1986) and whose intelligence (IQ) was representative of the general population. Consistent with other types of expert performance, their superior predictions of races were mediated by a complex mental representation. This representation enabled them to reason about many interacting factors in order to extract relevant information about a specific horse from its performance in previous races.

EXPERT PERCEPTUAL PERFORMANCE *Visual medical diagnosis* In a recent review of expertise in visual diagnosis of X-rays and skin disorders, Norman and coworkers (1992a) found only modest increases in accuracy for representative X-rays beyond that of medical residents with more than one year of daily experience with X-ray diagnosis. These investigators observed distinctly superior performance by experts only on difficult cases (Lesgold et al 1988, Wolf et al 1994). For skin disorders the accuracy of diagnosis increased uniformly as a function of expertise over both easy and difficult cases (Norman et al 1989b). On the basis of think-aloud protocols Lesgold et al (1988) were able to study expert radiologists' construction of an integrated mental representation of X-rays for complex cases. These experts were able to incorporate into their mental representation unusual features, such as dislocation of organs due to previous surgery, and other information about the patient's clinical history. Norman et al (1992a) found that correct as well as incorrect clinical histories influenced both the diagnosis of X-rays and identification of consistent visual information.

Increased expertise in visual diagnosis appears to be associated with more rapid perceptual identification of abnormal features at presentation times of 0.5 s (Myles-Worsley et al 1988) and 2.0 s (Lesgold et al 1988). Experts reached their correct diagnosis of skin disorders faster than novices but took longer on their incorrect decisions (Norman et al 1989b).

Other domains When expert judges or referees in sports are shown filmed sequences of sports events, their ability to make perceptually based judgments relevant to their specific expertise is superior to that of control subjects. Expert judges of gymnastics were better able to detect errors in gymnastic routines, but their incidental recognition memory for the performances was not different from that of novice judges (Ste-Marie & Lee 1991). Expert referees were no better than expert players and coaches in detecting that a foul had been committed in basketball, but they were more accurate in identifying the specific type of violation (Allard et al 1993). Expert coaches are better than novices in evaluating and describing filmed sequences of swimmers' swim strokes (Leas & Chi 1993) and the motor execution of shot putters (Pinheiro & Simon 1992).

EXPERT PERCEPTUAL-MOTOR PERFORMANCE *Typing* An expert's skill in typing can be elicited under standardized conditions with unfamiliar texts or even randomized orders of words (see Gentner 1988, Salthouse 1986 for reviews). In any particular instant, expert typists are looking well ahead in the text they are typing. The difference between the text visually fixated and the letters typed in a given instant (eye-hand span) increases with the typist's typing speed. By directing their perception ahead of the currently typed text, experts can prepare future keystrokes by moving their fingers in advance toward a desired location (Gentner 1988). The largest differences in speed between expert and novice typists are found for successive keystrokes made by fingers of different hands because experts who have had extended practice can prepare these movements in advance by overlapping movements (Gentner 1983, Salthouse 1984). When subjects are prevented from looking ahead at the text to be typed, the speed of expert typists is reduced nearly to that of novice typists (Shaffer 1973, Salthouse 1984).

Music Expert musical performance is typically displayed in the solo performance of a piece that the musician has extensively studied beforehand. A distinctive characteristic of expert musicians is their superior ability to reliably reproduce the timing and loudness variations in consecutive performances of the same piece (Ericsson et al 1993, Krampe 1994, MacKenzie et al 1983, Palmer 1989, Sloboda 1991). When experts are asked to violate the rules governing artistic interpretations of musical pieces (Repp 1992), the reproducibility of their performance declines (Clarke 1993). Furthermore, expert musicians can better maintain independent timing in both hands when playing music (Shaffer 1981) or tapping (Summers et al 1993) than less accomplished musicians.

Expert musicians have also been studied under standardized conditions in which they play (sight read) unfamiliar music. Similar to typing, individual differences in sight-reading were correlated with differences in eye-hand span (Bean 1938, Sloboda 1984). When the sight-reading of expert pianists was paced while they accompanied a solo instrument, Ericsson & Lehmann (1994) found systematic individual differences that were predicted only by relevant training opportunities in the accompaniment of choirs and soloists.

Juggling In a task analysis of juggling, Beek (1989) found that the possible movement patterns for juggling a certain number of balls are highly constrained. This task characteristic explains the high consistency in world-class jugglers' methods and timing. From careful analysis of juggling performance, Beek found that sustained juggling is not a steady state but instead requires continuous corrections and adjustments. In some of his experiments Beek (1989) occluded parts of a juggler's visual field and found that the juggler needed to see only the apex of the ball's trajectory to maintain successful control of the juggling.

Sports The demands on expert perceptual-motor performance in sports nearly always include requirements for speed, very precise motor responses, or both. As the level of competition increases in sports requiring speeded responses, the available time to produce responses decreases because of the greater strength and speed of elite opponents. Elite athletes have to select responses on the basis of advance perceptual cues. Even the very best cricket players cannot make any major corrections within the last 190 ms before ball contact (McLeod 1987), as shown by experimental studies in which these players had to hit pitched balls that bounced unpredictably on a rough surface. During the last 200 ms before ball contact, athletes extract very limited information, as Lamb & Burwitz (1988) demonstrated. In their experiment, athletes catching tennis balls shot by a "cannon" indoors were able to perform this task without a reliable decrement when the light was turned off during this time.

When confronted with representative situations, elite athletes can produce the required reactions faster (Helson & Pauwels 1993) and make anticipatory movements earlier than less skilled athletes (see Abernethy 1987b for a review). The temporal precision required to successfully complete an action in sports is very high, and in some types of hitting the precision may be as high as ±2 ms (McLeod & Jenkins 1991). To attain such a level of precision, athletes' motor systems can adjust the force in hitting movements as late as 50 ms prior to ball/bat contact. For example, elite table tennis players control the temporal variability in initiating a forehand drive to produce the highest timing accuracy at ball contact (Bootsma & van Wieringen 1990). In fact, for some hitting skills the expert players' backward swing phase is actually more variable than that of novices, although temporal variability at ball contact is less for experts (see Abernethy & Burgess-Limerick 1992 for a review).

In contrast to researchers in most of the other domains reviewed in this chapter, researchers in sports—with few exceptions—have not collected concurrent and retrospective verbal reports on expert performance on representative tasks. Think-aloud protocols show that expert snooker players engage in deeper planning than novices when evaluating a configuration of billiard balls (Abernethy et al 1994), and unexpected recall by expert miniature-golf players for the nature of their shots has been found to be superior to that of less skilled players (Bäckman & Molander 1986).

EXPERT MEMORY PERFORMANCE The highest levels of memory performance have been observed in professional mnemonists. Researchers have also studied some types of expert performance, such as mental multiplication and memorization of dinner orders, in which exceptional memory is an integral part.

The pioneering research on individuals with exceptional memory was conducted by Binet (1894) who examined the performance of two subjects, Inaudi and Diamondi, on standardized memory tasks for digits. Since then, the memory performance of many exceptional individuals has been studied in the laboratory, e.g. S (Luria 1968), VP (Hunt & Love 1972), TE (Gordon et al 1984), Rajan (Thompson et al 1993), and many others (Brown & Deffenbacher 1988). Reviews of this laboratory research (Ericsson 1985, 1988) show that truly exceptional memory performance is typically restricted to a single type of material, often sequences or matrices of digits. With sufficiently rapid presentation, memory performance decreases dramatically and approaches the normal range, even for this preferred type of material. Although all of the exceptional individuals were found to have engaged in prior training and practice with their preferred material, the strongest evidence for the acquired nature of exceptional memory comes from training studies with college students.

After 50–100 h of practice on the digit-span task, several students surpassed the performance of most exceptional subjects—20 digits (Chase & Ericsson 1981, 1982). With further practice, two subjects attained the highest digit spans ever recorded: 82 (subject SF) (Chase & Ericsson 1982) and over 100 digits (subject DD) (Staszewski 1988a), respectively. They matched and surpassed the performance of the exceptional subjects when tested on the previously used memory tasks involving digit matrices, and their pattern of recall was indistinguishable from that of exceptional subjects (Ericsson & Chase 1982). Subsequently, Chase & Ericsson (1982) proposed the theory of skilled memory, which accounts for the superior memory performance of both trained and exceptional subjects. Skilled memory theory specifies how subjects can rapidly encode a particular type of material in long-term memory (LTM) by associating this material with pre-existing knowledge and patterns. Subjects maintain the accessibility of the stored information in LTM through previously generated associations between the encoded information and a reusable retrieval structure acquired during prior training. Recently Richman et al (1995) have proposed an explicit simulation model of exceptional digit-span performance that is able to reproduce virtually all aspects of DD's observable memory performance, including verbally reported information.

Chase & Ericsson (1982) proposed that if students can acquire memory skills enabling them to use LTM in memory tasks with rapid presentation rates [originally designed to measure short-term memory (STM)], then the mechanisms of skilled memory can be adapted to expand working memory in many types of expert performance. The superior memory of waiters and waitresses for drink orders (Bennett 1983) and the exceptional memory of a waiter (JC) for dinner orders (Ericsson & Polson 1988a,b) support this hypothesis and were successfully captured by laboratory analog tasks. Verbal reports and—in the case of JC—a series of experiments show that superior memory performance is mediated by acquired mechanisms consistent with skilled memory theory.

Some tasks, like multiplication or the addition of a long series of large numbers, are easy to perform with paper and pencil but difficult and very demanding of memory when carried out mentally. Expert mental calculators acquire their skill through extended, specific training on the task (Staszewski 1988b). Such experts have to retain several intermediate products that are given a distinctive memory encoding to avoid proactive interference (Chase & Ericsson 1982, Staszewski 1988b). Extended working memory in mental multiplication and abacus calculation (Hatano & Osawa 1983) was accounted for by Ericsson & Kintsch (1995) in an extension of skilled memory theory that distinguished several types of long-term working memory (LT-WM) involving different encoding methods with differential accessibility and storage characteristics.

In sum, expert memory performance is not an automatic consequence of domain-specific experience but rather requires the acquisition of specific memory skills tailored to the demands of working memory by the particular activity.

SUMMARY Investigators have been able to capture and study in the laboratory the mechanisms that mediate expert performance in many domains. On the most general level, captured expert performance reflects many different types of complex mechanisms acquired to meet the specific demands of the tasks in a domain of expertise. Hence, traditional accounts of expert performance in terms of pattern-based, automatic retrieval of actions are insufficient and have to be extended.

In perceptual performance, experts extract new and more informative perceptual features to improve performance. To achieve high levels of perceptual-motor performance, experts must circumvent reaction-time limits for serial discrete motor responses by advance preparation and overlapping of movement production, reflected in increased eye-hand spans in typing and music. In many sports, expert levels of motor performance require remarkable timing, often within the millisecond range. This performance appears to be mediated by dynamic adjustments of the motor system as late as 50 ms prior to the critical event, such as the contact between ball and racquet. Mnemonists and trained memory experts show that speed of storage in LTM can be dramatically improved and that the limited capacity of general working memory, based on STM, can be extended in specific activities with the acquisition of domain-specific LT-WM.

Contrary to the belief that expert performance is highly automatized, most types of expert performance are mediated by reportable thoughts involving planning, reasoning, and anticipation. Even perceptual-motor activities have been successfully monitored with concurrent and retrospective verbal reports that reveal considerable planning and generation of expectations (for snooker, see Abernethy et al 1994; baseball, McPherson 1993b; tennis, McPherson & Thomas 1989; control of simulated cargo ships, Anzai 1984; other types of process control, see Ericsson & Simon 1993 for a review). That experts' incidental memory for task-relevant information is superior to that of novices also implies that most forms of expert performance remain mediated by attention-demanding cognitive processes.

Thus, the analysis of expert performance shows that experts increase their level of performance by structural changes of performance. The ability of experts to exceed usual capacity limitations is important because it demonstrates how particular acquired skills can supplant critical basic limits within a restricted and specific type of activity.

The Study of Components of Expert Performance

To test the hypothesis that expert performance is an extreme adaptation to task constraints mediated through deliberate practice, it is essential to preserve all of the relevant constraints in the tasks studied. On the other hand, the complexity of expert performance makes it desirable for investigators to identify perceptual or memory components and associated tasks in which these components can be studied separately. However, to gain useful information about the structure of components, it is important to capture the contextual demands of these components within the overall expert performance.

The problem with studying component tasks is that high performance on a given task can be attained independently of expert performance on the task as a whole. Thousands of hours of study are required to attain the skill level of chess masters. Nevertheless, Ericsson & Harris (1990) and Ericsson & Oliver (1989) showed that an individual with essentially no prior knowledge of chess could learn to recall briefly presented chess positions at a level matching that of chess masters after only 50 h of practice in memorizing chess positions. A detailed analysis of chess pieces showed that the trained subjects focused on perceptually salient pawn chains, whereas chess masters recalled the critical pieces in the center of the chess board. Hence, a chess masters' performance level can be attained in a manner that is insensitive to the constraints of extracting the most important information about the chess position.

RAPID PERCEPTION OF EXPERTS The highly interactive nature of competitive sports and their demands for rapid and complex motor responses makes experimental investigation difficult. Hence, investigators have filmed situations in sports from the vantage point of such athletes as a receiver of a tennis serve. To assess the earliest point at which an athlete can predict where, for example, a tennis serve will land, the experimenter can prematurely stop the film sequence at various points (including points prior to the time that the server's racquet has made contact with the ball) and ask athletes to make their predictions. Usually, accuracy and RT for the decision is recorded.

Experts' superior predictions based on early perceptual cues (see Abernethy 1987b, 1991 for reviews) have been observed for the landing location of serves in badminton (Abernethy & Russell 1987b), types of serves in tennis (Goulet et al 1989), types of pitches in cricket (McLeod 1987), direction and force of shots in squash (Abernethy 1990), placement of shots on the goal in field hockey (Starkes 1987), and predictions of passes in volleyball (Wright et al 1990). Investigators have used several methods to identify which perceptual cues experts rely on for their successful predictions. One method has been to record eye fixations during the viewing of a film (see Ripoll 1991 for a review). For example, the pattern of expert tennis players' eye fixations differed from that of novices during the early phases of the tennis serve (Goulet et al 1989). Another approach has been to manipulate the frames of the film to systematically mask specific types of stimuli, such as the server's arm or racquet. For example, occluding the arm of the server degraded the accuracy of prediction in expert badminton players (Abernethy & Russell 1987a).

Investigators have found evidence for other domain-specific perceptual skills in experts, such as detecting the presence or absence of a volleyball (Allard & Starkes 1980) and counting pieces and detecting the presence of "check" in chess (Saariluoma 1985). These studies suggest that local features mediated the superiority of experts over nonexperts because the advantage in reaction time was preserved even for randomly rearranged stimuli, although the performance of both experts and novices was typically worse for those stimuli.

These findings show that not only does the speed of experts' perceptual process increase, but experts can circumvent the demand for rapid reactions by accurate anticipation based on advance perceptual cues. Furthermore, the experts' ability to accurately report anticipated outcomes refutes traditional claims that experts completely automate the execution of perceptual-motor performance.

SUPERIOR MEMORY OF EXPERTS Experts in most domains display superior memory on unexpected recall tasks, which implies that accurate memory for important stimuli is a natural consequence of expert processing. In this section we review studies on memory performance with explicit and controlled memory tasks. In these studies, only the pioneering work on chess conforms to our proposal that investigators first identify a component of intact expert performance and then design tasks to investigate that particular component.

In their classic study, Chase & Simon (1973) followed up de Groot's (1946/1978) finding that chess experts' superior memory is a natural consequence of their examination of a chess position. Instructing chess players to memorize briefly presented chess positions, Chase & Simon showed that these players' superior recall for regular chess positions reflected chess-specific knowledge; their recall was uniformly poor for randomly rearranged positions. Because Chase & Simon presented the stimuli for only 5 s, they inferred that recall reflected only storage in STM. All chess players perceived patterns of chess pieces (chunks), but the number of chunks did not differ systematically between experts and novices and it fell within the traditional limits of STM (Miller 1956).[3] Chase & Simon (1973) attributed higher recall with increased expertise to the availability of more complex patterns of chess pieces (chunks) in LTM, where on the average each of the experts' chunks corresponded to a larger number of pieces. Their basic finding that experts exhibited superior memory for representative structured stimuli but not for recall of random, unstructured stimuli was replicated in chess (see Charness 1991 for a review) and in many other domains: bridge (Charness 1979, Engle & Bukstel 1978), GO (Reitman 1976), Othello (Wolff et al 1984), snooker (Abernethy et al 1994), medicine (Norman et al 1989a), electronic circuit diagrams (Egan & Schwartz 1979), computer programming (McKeithen et al 1981), dance (Starkes et al 1987), basketball (Allard et al 1980, Allard & Burnett 1985, Starkes et al 1994), field hockey (Starkes & Deakin 1984, Starkes 1987), volleyball (Borgeaud & Abernethy 1987), figure skating (Deakin & Allard 1991), and football (Garland & Barry 1991).

Further research uncovered several potential exceptions. Experts' memory is nearly always reduced for randomly rearranged stimuli but is still superior to novices' memory. This finding held true for random chess configurations (Lories 1987, Saariluoma 1989), process-control displays (Vicente 1992), random musical notation (Halpern & Bower 1982, Sloboda 1976), randomly rearranged computer programs (Adelson 1981, Shneiderman 1976), unstructured game diagrams in volleyball (Allard & Burnett 1985), unstructured stimuli in modern dance (Starkes et al 1990), and nonsense ballet movements (Smyth & Pendleton 1994). Nor did experts show superior memory for information, such as melodies auditorily presented to musicians (Sloboda & Parker 1985), text presented to expert actors (Intons-Peterson & Smyth 1987, Noice 1993), and noncontour maps presented to map experts (Gilhooly et al 1988).

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[3] This mechanism predicts superior memory for individuals at many different levels of skill. In this section we therefore include some studies of subjects whose performance does not meet our criterion for expert-level performance.

Finally, memory for medical information does not increase uniformly with expertise (Patel & Groen 1991), and for some types of information about computer programs, expert programmers recall even systematically less than novices (Adelson 1984).

We propose that experts' superior memory is not general across all types of information in a domain but reflects selective encoding of relevant information and mechanisms acquired to expand the functional capacity of the experts' working memory.

Chess Chase & Simon (1973) gave an elegant account of the superior memory of chess experts in terms of complex chunks in STM, but this account has not been supported by subsequent research. Charness (1976) and Frey & Adesman (1976) showed that even briefly presented information is stored in LTM and not in STM. More recently, Cooke and coworkers (1993) and Gobet & Simon (1995b) extended these findings, showing that highly skilled chess players can recall substantial amounts from the comparably fast presentation of up to nine different chess positions.

Highly skilled chess players cannot only recognize isolated patterns but also construct an integrated representation of the position. This representation consists of interconnected chunks (Chi 1978) with a hierarchical structure (Freyhof et al 1992) and relations to familiar types of chess games (Cooke et al 1993, Gobet & Simon 1995b). It provides access to relevant information about appropriate moves and distinguishes memory of different chess positions in LTM. However, a highly interpreted representation does not facilitate systematic search and exploration of possible future moves. Having found that for memorized chess positions a chess master could very rapidly retrieve the piece in any location of the board, Ericsson & Oliver (in Ericsson & Staszewski 1989) proposed that chess masters have acquired a retrieval structure that mentally represents all the different locations of the chess board, and they can thereby manipulate and encode the location of individual chess pieces directly. Furthermore, Saariluoma (1989) showed that chess masters can store regular and random chess positions when each position is verbally presented as a sequence of chess pieces with their respective locations on the board. Finally, chess masters can play blindfold chess games—without a perceptually available chessboard—at close to their normal strength (Holding 1985). An experimental study by Saariluoma (1991) showed that a grand master under blindfold conditions could maintain the chess positions for 10 simultaneous chess games in memory with virtually no errors.

Recently, Ericsson & Kintsch (1995) proposed that chess experts extend their working memory capacity, acquiring long-term working memory (LT-WM) skills to support the planning and evaluation of chess positions. LT-WM is a single mechanism that accounts for experts' superior performance on memory tests for chess positions as well as for other memory-demanding activities for which Chase & Simon (1973) originally proposed a separate mechanism, namely the Mind's Eye. The empirical evidence favors an account based on LT-WM for also explaining superior memory of experts in other games with similar demands for planning, such as bridge, GO, Othello, and snooker.

Medicine The superior memory of medical experts reflects their abilities to select critical information (Groen & Patel 1988) and to summarize relevant detailed information about patients by making higher-level inferences (Schmidt & Boshuizen 1993). Given that the criterion for expert performance is superior diagnostic accuracy, not the reproduction of presented details, the acquisition of higher-level concepts and an associated working memory system is an adaptive response to the demands of effective reasoning about alternative diagnoses. The detailed structure of the working memory of medical experts is discussed by Patel et al (1994) and Ericsson & Kintsch (1995).

Other domains In general, analyses of representative demands of expert performance in a domain yield reasonable predictions of the superior performance experts ought to display for a particular memory task. For example, the critical demand for anticipation and coordination in team sports requires that elite athletes continuously update their representation of the current situation of a game, and this skill is reflected in their superior memory for representative game situations (Allard & Starkes 1991). The important role of higher-level plans for the overall function of computer programs accounts well for expert computer programmers' superior memory for the general structure of programs and for their inferior memory for details (Adelson 1984). Expert actors (Noice 1991) study theatrical scripts to portray the integrated behavior of a character, and expert musicians create personal interpretations of music, tasks for which immediate memory for briefly presented information and rapid rote memorization are not critical constraints for these types of expert performers.

Another general mechanism that mediates improvement in creation of new memory traces in LTM, especially with slower presentation rates, is the extent of associated knowledge and patterns. Expert knowledge of a domain leads to superior recall for information relevant to the domain but not for other types of information (Chiesi et al 1979, Morris et al 1985, Schneider et al 1989, Spilich et al 1979). Superior recall even for arbitrary information associated to concepts of the domain of expertise has been demonstrated (Bellezza & Buck 1988). It is likely that this type of effect of general knowledge can—at least partially—explain experts' superior memory even for randomly arranged versions of stimuli in some domains, such as modern dance, volleyball, and music. Finally, superior memory performance can in some cases be mediated by knowledge through skilled guessing, especially when the guess is based on partially recalled information (de Groot 1966, Egan & Schwartz 1979).

Summary The vastly superior memory of experts for briefly presented information appears to reflect memory skills and LT-WM that they acquire to support many important activities, such as planning, reasoning, and anticipation of future events. Future investigations concerning experts' superior memory should therefore carefully analyze the demands and function of memory in intact expert performance.

RELATING COMPONENTS TO CAPTURED EXPERT PERFORMANCE Once a component of expert performance has been captured by specifically designed tasks and its structure has been successfully analyzed, it is important to relate it to the intact expert performance. Lacking complete simulation models of expert performance, investigators have relied on correlational techniques, but estimating the strength of the relation between performance on the component task and expert performance goes beyond the standard paradigm of contrasting the performance of extreme groups (experts vs novices). It requires either representative samples of performers or homogenous samples of expert performers.

In representative samples, Pfau & Murphy (1988) and Charness (1981b) found that chess ratings were reliably predicted by memory for chess positions. Pfau & Murphy (1988) found that, not surprisingly, the ability to select chess moves, the defining task for measuring expert performance, was an even better predictor. Charness (1979, 1983, 1987) found that characteristics of generating bids for a bridge hand had a modest correlation with bridge skill in a representative sample. Underwood et al (1994) were able to decompose the skill of solving crossword puzzles into a number of component tasks. Individual differences in the ability to solve crossword puzzles were then accurately predicted by performance on the tests of component skills.

CONCLUSIONS

Expert and exceptional performance is highly reproducible and, when compared with the performance of novices, has yielded the largest reliable differences observed by behavioral researchers among healthy adults. In chess, sports, and many other domains with thousands of active participants, individuals attain internationally recognized levels of exceptional performance only after spending about 10 years in intense preparation. In several domains expert performers engage in deliberate practice for around 4 h per day, a level that appears to be the maximum individuals can sustain on a daily basis for many years (see Ericsson et al 1993 for a review).

The conclusion that expert performance results from extended, deliberate practice differs from previously held ideas about the roles of talent and expertise. We have found that, with the single exception of height, current evidence for domain-specific characteristics (talent) among expert performers can be better accounted for by extended intense practice, which causes physiological, anatomical, and even neurological adaptations in the body. As for expertise, the levels of performance individuals attain after years of experience alone are much lower than those of experts who have adhered to regimens of careful training and practice.

In contrast to skilled activities that can be performed by rote, most types of expertise—even athletic performance—continue to be mediated by cognitive processes such as monitoring, planning, reasoning, and anticipating. For example, elite marathon runners report that they continuously monitor their physiological state and the effectiveness of their running, whereas novice runners deliberately think about things unrelated to their running to minimize their experience of pain (Morgan & Pollock 1977, see O'Connor 1992 for a review).

Expert performers acquire mechanisms for internally representing their current situation as a precondition for planning, reasoning, anticipating, and controlling motor production. As demands on speed and accuracy in a particular activity increase, expert performers face new learning tasks. Continued successful learning is necessary for experts to achieve a level of performance higher than their current level. For example, although many skilled typists have been able to automatize the level of performance they have already maintained (Shaffer 1975), research shows that they must commit their full attention and engage in active learning to further increase their typing speed (Book 1925a,b). Many of the mechanisms that mediate an expert's current performance also enable that expert to improve performance in response to feedback. Further analysis of the structure of expert performance and of the learning processes by which experts improve will provide investigators with the most promising information about the potential for and limits of human learning and adaptation.

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