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EXPERTISE IN CHESS

Fernand Gobet, Brunel University

Neil Charness, Florida State University

<A> Historical Background

Chess has long served as a model task environment (Drosophila -- fruit fly) for research into psychological processes (Charness, 1992). Some of the earliest systematic work on individual differences in imagery (Binet, 1893/1966; 1894), memory (Djakow, Petrowski, & Rudik, 1927) and problem solving (de Groot 1946/1965) took place in the domain of chess. Cleveland (1907) was one of the first to identify the importance of complex units, now called chunks, in skilled play, and speculated that intellectual abilities might be poor predictors of chess skill, even providing the score of a game played with a "mentally feeble" individual.

De Groot ushered in the modern era of investigation (1946/1965) using small groups of expert and grandmaster level players in experimental studies. Of de Groot's many findings, it was the dissociation between thinking skills and perceptual-memory skills that laid the groundwork for subsequent research. When asking players to think aloud while they attempted to choose the best move in an unfamiliar position, de Groot discovered that, contrary to popular lore, the most proficient players did not think further ahead than less skilled practitioners. It was a different experimental task -- memory for briefly presented chess positions -- that markedly differentiated skill levels. De Groot found that skilled players proved to have strikingly superior memory for chess positions after brief presentations (2-15 s), compared to their less proficient counterparts. De Groot interpreted these findings to support the importance of knowledge and perceptual organization principles over search algorithm differences in explaining how experts chose better moves.

Follow-up research by Chase and Simon (1973a, 1973b) revealed that the perceptual/memory advantage for skilled players was only obtained when they viewed structured chess positions. When pieces were randomly arranged on the board, there was little, if any, memory advantage for a Master player compared to a Class A player, compared to a novice player. This dissociation, a finding that has become a touchstone of the expert performance approach in many other domains, suggested that acquired patterns not innate abilities accounted for skill differences. On the basis of these data and those gathered in other experiments and in simulation studies, Chase and Simon proposed their highly influential chunking theory of skilled performance in chess. That theory and its subsequent refinement has had a significant impact on expertise research in general and that on games in particular (see Gobet, de Voogt, & Retschitzki, 2004, for an extensive coverage on board games, and Charness, 1989, for a presentation of the data on bridge.).

<A>Brief Description of the Game and the Rating System

Chess is a game played by two opponents using an initial configuration, the starting position, consisting of 32 chess pieces placed on an 8x8 square chessboard.

The rules of chess are sufficiently simple that children can be taught them at a very young age (4 or 5 years old). Child prodigies are not uncommon and teenagers have been able to compete at the highest level. (Nineteen year-old Ruslan Ponomariov was crowned world champion in 2002.) Chess is sufficiently difficult to play well that it took about 40 years of effort by computer scientists to program computers to compete on an equal level with the best human players.

Another important feature for chess is the existence of a sophisticated measurement scale for evaluating chess skill based on performance in chess tournaments. The Elo rating scale, available since the mid 1960s (Elo, 1965; Elo, 1986) is open-ended, starting at a nominal value of zero and extending upward, with a nominal class interval (standard deviation), of about 200 rating points. The world's best players today hover above 2800 rating points with Grandmaster level at approximately 2500 rating points, International Master at about 2400 points and Master at about 2200 points. This interval level rating scale enables fine-grained examination of the relation between expertise and a variety of indicators of psychological processes. Measurement of expertise on this fine a scale remains a central problem for many other domains discussed in this volume.

For instance, a psychometric approach to chess skill (e.g., Van der Maas & Wagenmakers, 2005) can capitalize on the chess rating scale to examine how well it correlates with different markers of psychological processes such as measures of memory, problem solving, and motivation. Early efforts at understanding skill in chess implicitly made use of this correlates approach for measures of attention (Tikhomirov & Poznyanskaya, 1966), imagery (Milojkovic, 1982; Bachmann & Oit, 1992) and personality (Charness, Tuffiash & Jastrzembski, 2004).

In this chapter we focus on a process model approach to understanding expertise in chess. Our goal is to shed light on the process of how players choose the best moves to play in a chess game, starting from early perceptual processes and tracing forward to the search processes first described by de Groot. We outline where skill differences arise within such processes. We describe computer simulation models that capture some of the features of skilled performance by chess players. We also describe how human players acquire the knowledge necessary to play chess expertly.

<A>Information Processing Models of Choosing a Good Move: The Trade-Offs Between Knowledge And Search

The goal of a chess player is to choose the best possible move. Often, when playing through standard openings, the best move is dictated by knowledge from published analyses, such as the *Encyclopedia of Chess Openings*. Sometimes, detecting the best move in a sequence of exchanges of pieces is simple enough that even novices quickly find it. Much of the time, the best move is non-obvious and the player must decide based on a search process that evaluates a candidate move in terms of potential future positions reached via a branching tree of available moves for the two sides.

Search is difficult because of the enormous number of possible moves stemming from the opening position. Even master players who can use well-tuned recognition processes to winnow the possible base moves down to 3 or 4 plausible alternatives at each point in the tree face a dilemma. The number of possible moves, computed as breadth raised to a power equal to depth, is 4^{76} moves, given that the average master game lasts about 38 moves or 76 plies (moves for each side). So, both computers and humans must search selectively among the alternatives using a variety of heuristics (Newell & Simon, 1972) to decide when a node reached in search can be properly evaluated.

Given the relatively slow rate at which moderately skilled players can generate analysis moves, estimated in Charness (1981b) to be about 4 moves per minute, it is obvious that much of the time that human players spend is not in generating all possible moves (perhaps taking a move per second) but in generating moves selectively and using complex evaluation functions to assess their value. Computer chess programs can achieve high-level play by searching many moves using fast, frugal evaluation processes that involve minimal chess knowledge to evaluate the terminal positions in search. Deep Blue, the chess program that defeated World Champion Garry Kasparov in a short match in 1997, searched hundreds of millions of positions per second. Today's leading microcomputer chess programs that have drawn matches with the best human players, have sophisticated search algorithms and attempt to use more chess knowledge but still generate hundreds of thousands or millions of chess moves per second. Generally, chess programs rely on search more heavily than knowledge; for humans it is the reverse. Yet, each can achieve very high performance levels because knowledge and search can trade off (Berliner & Ebeling, 1989).

Because expert humans do so little search, yet still manage to find strong chess moves, attention has shifted from investigating search processes to understanding the role of pattern recognition processes in move selection. As de Groot noted, skilled players use their knowledge about chess configurations to generate plausible moves for limited searching. We now focus on understanding the perceptual mechanisms that support this rapid perception advantage.

<B>Tracing Expertise Differences in Perception and Attention with Eye-Tracking Techniques

Jongman (1968) initiated work on perceptual skill differences by examining eye movements of expert and less expert players, though his results became widely accessible with the re-analysis published by de Groot and Gobet (1996). These researchers showed that in a memorizing task, where players were given a few seconds to examine an unfamiliar chess position, better players fixated more on the edges of squares than weaker players did. Also, better players were more likely to have greater distances between fixations, implying that they were able to encode more widely about a fixation than weaker players. Experts also made shorter duration fixations than did weaker players implying faster encoding.

Reingold and colleagues confirmed the larger visual span for experts using a variety of tasks. Using a gaze-contingent paradigm that manipulated the number of visible squares, Reingold, Charness, Pomplun, and Stampe (2001) showed that more skilled players needed a larger area around fixation to detect changes in successively displayed chess positions in order to match performance under unlimited view of the whole board. This was only true for structured, not random chess positions. This result suggested that better players had a larger visual field from which they could extract chess relationships. In a second experiment, the authors noted that when players made a simple determination of whether a King was in check by an attacking piece on a minimized chessboard (3 x 3 squares), experts required fewer fixations to decide and these fixations were more likely to be between pieces (on empty squares), compared to intermediate-level players. (See also Fisk & Lloyd, 1988, and Saariluoma, 1985, for data on perceptual processes in simple decision tasks.)

In a choose-a-move task using full chessboards, Charness, Reingold, Pomplun and Stampe (2001) demonstrated that experts made fewer fixations per trial and those fixations were more widely spaced out across the board and again, more likely to be between than on chess pieces. More importantly, for the first five fixations, experts were more likely to fixate on relevant squares (rated as relevant by a strong International Master player). This very early advantage (within the first second of exposure to a new position, given that fixations average about 250 ms each for both experts and intermediate players) testifies to the importance of pattern recognition processes in providing a better representational structure. Given this perceptual head start, experts also chose better moves and did so more quickly than their less expert counterparts.

Reingold, Charness, Schultetus and Stampe (2001) used a Stroop-like interference task within a 5 x 5 square segment of a chessboard to demonstrate that expert players appear to extract chess relations in parallel whereas weaker ones appear to shift attention and encode the same relations serially. In a two-attacker situation, supplying a cue about which piece to attend to provided an advantage in response time to less skilled players, but no advantage to expert players because the latter appeared to encode both attack relations simultaneously.

In summary, experts rely on a rich network of chess patterns stored in long-term memory structures (or long-term working memory, Ericsson & Kintsch, 1995) to give them a larger visual span when encoding chess positions. They encode chess information far more quickly and accurately than non-experts. Within the first second of exposure to a new position, experts are examining salient squares on the chessboard and extracting, in parallel, chess relationships critical to choosing good moves. In later sections we outline how CHREST, a computer simulation program, acquires and utilizes such chess patterns (templates and chunks).

<B>Memory Processes

As early as Binet (1894), and in particular in de Groot's work, knowledge has been identified as a key component of chess expertise. In order to understand how knowledge (held in memory) mediates skill, a substantial amount of research has been carried out on chess players' memory. Domains of interest include memory for static positions, memory for moves and sequences of moves [discussed in the section on blindfold chess], and the structure and contents of long-term memory (LTM), including the number of chunks necessary to reach expert performance. In many cases, experimentation has been carried out in concert with computational modeling.

<C>Memory recall for positions: Chase and Simon's key results. While both Binet and De Groot highlighted the key role of knowledge in chess expertise, one had to wait until Chase and Simon's work in 1973 to have a detailed theory of expert memory. Extending De Groot's study showing a striking skill effect in the recall of game positions, Chase and Simon carried out detailed analyses to identify what were

the building blocks of chess knowledge. In a copy task, they analysed the pattern of eye fixations on the stimulus board, as well as the way pieces were grouped during reconstruction. Comparing these results with those obtained in a recall task, they inferred that pieces placed within 2 seconds and sharing a number of semantic relations were likely to belong to the same chunk. (These results were replicated by Gobet & Simon, 1998, and Gobet & Clarkson, 2004.) They proposed that skill did not reside in differences in short-term memory (STM) capacity or encoding speed, but in the number of chunks held in LTM memory. These chunks give access to information such as what move to play, what plan to follow, and what evaluation to give to (part of) the position. Thus, their theory explained both why masters choose better moves in spite of their selective search (because chunks enable them to identify the key features of a position, and guide search during look-ahead) and why they perform better in a memory task (because they can partition the position in relatively large groups of pieces, unlike weaker players who have to use more smaller groups, which overtax STM). Some of these ideas were implemented in a computer program, MAPP (Simon & Gilmartin, 1973), which simulated recall up to expert level.

<C>Problems with the chunking theory lead to the template theory. A number of experiments have helped refined Chase and Simon’s theory. Charness (1976) showed that the presence of an interfering task reduced recall only marginally, which runs counter the assumption of a slow encoding in LTM. Several authors (Frey & Adesman, 1976; Cooke et al., 1994; Gobet & Simon, 1996a) have shown that players can remember multiple boards reasonably well, which again highlighted a weakness of the original chunking theory.

These results, as well as the fact that verbal protocols reveal that masters use larger structures than the chunks identified by Chase and Simon (e.g., De Groot, 1946; De Groot & Gobet, 1996; Freyhoff, Gruber, & Ziegler, 1992; Gobet, 1998a), led Gobet and Simon (1996a, 2000) to revise the chunking theory. Their template theory aimed to remedy these weaknesses, while keeping the strengths of the original chunking theory. It also aimed to show how high-level, schematic structures (templates) can evolve from perceptual chunks. As with the chunking theory, chunks and now templates are crucial in explaining how players access relevant information by pattern recognition. The computer program CHREST (Chunk Hierarchy and REtrieval STructures) implements aspects of the template theory. CHREST consists of an STM, an LTM indexed by a discrimination net, and a simulated eye. Each cognitive process has a time cost; for example, it takes 50 ms to place a chunk in STM, and 8 seconds to create a new chunk. During the learning phase, the program automatically acquires chunks and templates by scanning a database of positions taken from masters' games. During the testing phase, it is placed in the same experimental situation as human participants. The program has simulated various characteristics of players' eye movements (De Groot & Gobet, 1996), the details of reconstruction in recall experiments (Gobet, 1993; Gobet & Simon, 2000; Gobet & Waters, 2003), as well as the way novices learn to memorize chess positions (Gobet & Jackson, 2002). Beyond chess, variants of the program have been applied to memory for computer programs, use of diagrammatic representation in physics, concept formation, and children's acquisition of language (Gobet et al., 2001).

<C>*Random positions*. While Chase and Simon (1973a, b) found no skill difference in the recall of random positions, Gobet and Simon (1996b) show that later studies did

in fact find such a difference, although the effect is rarely significant due to the low statistical power within these studies. This skill effect remains across a wide range of presentation times (from 1 second to 60 seconds; Gobet & Simon, 2000) and with positions where the location as well as the distribution of pieces is randomized (Gobet & Waters, 2003). These results are consistent with the chunking and template theories, which predict that strong players, who have more chunks, are more likely than weaker players to recognize some patterns even with random positions. Indeed, computer simulations (Gobet & Simon, 1996b; Gobet & Simon, 2000) confirmed these predictions.

<C>*New estimates of the vocabulary of the master.* Based upon computer simulations with MAPP, Simon and Gilmartin (1973) estimated that one needed to acquire from 10,000 to 100,000 patterns to reach master level in chess. These estimates have led to several experiments, in part because Holding (1985) argued that a much smaller number was required if one assumed that the same chunk could encode the same constellation of pieces placed at different locations of the board. Saariluoma (1994) modified positions by swapping quadrants, and Gobet and Simon (1996c) modified positions by taking their mirror images along various axes of symmetry. Both found that these manipulations affected recall, which runs counter to Holding's predictions but supports the original chunking theory. Computer simulations with CHREST show that at least 300,000 chunks are required to reach grandmaster level, even with the presence of templates, which were not part of the chunking theory.

<C>*Recognition experiments*. In the past, few studies have been carried out using a recognition paradigm (e.g., Goldin, 1978, 1979; Saariluoma, 1984). This pattern has not changed in recent years, and we could find only one study using this technique. McGregor and Howes (2002) presented positions for either 9 or 30 s, asked participants to evaluate them, and later carried out a recognition test. In one experiment, the positions presented during the recognition phase were distorted by shifting either all pieces or a single piece one square horizontally. Two further experiments used a priming technique during the recognition phase: a piece from the target position was shown for two seconds; this was followed by a second piece, and participants indicated whether they thought it was in the target position. The two pieces shared either a relation of attack/defence or a relation of proximity. McGregor and Howes found that class A players used information about attack/defence more often that information about the location of pieces.

<B>*Problem Solving Processes.*

Today's chess-playing programs benefit from the enormous progress in refining computer search algorithms. Running on off-the-shelf microcomputers, they are of world championship caliber. One could argue that knowledge about human problem solving processes in chess has lagged the efforts in artificial intelligence, though steady progress is evident. De Groot (1946/1965), Newell and Simon (1972) and Wagner and Scurrah (1971) have generated many of the explicit models that describe the heuristics used by humans to manage search.

<C>*De Groot's study*. De Groot (1946) asked his participants to think aloud when choosing their next move in a problem position. The quantitative and qualitative measures he extracted from the verbal protocols provided important empirical information about chessplayers' thinking. We will use some of the main phenomena discussed by de Groot to organize this section.

<C>*Macrostructure of Search in Chess*. De Groot (1946) found few differences in the macrostructure of search between world-class grandmasters and relatively strong players (Experts). Surprisingly, during their search, players from both skill levels tended to search at similar depth, to consider the same number of positions, and to propose similar numbers of candidate moves. But there were differences as well: the grandmasters chose better moves than the Experts, they generated moves faster, they reached a decision faster, and, during their search, they examined moves and sequences of moves that tended to be more relevant.

Holding (1985) argued that de Groot's (1946) small sample (5 grandmasters and 5 Experts) may have concealed existing skill differences. Supporting Holding's view, some skill differences were found with samples including weaker players (e.g., Charness, 1981b; Gobet, 1998b; Saariluoma, 1992). Charness (1981a) suggested that depth of search increases up to Expert level, after which it stays uniform. Charness (1989) conducted a 9-year longitudinal investigation of a Canadian player who advanced (in power law fashion) from an average level performance (1600 rating points) to International master level performance (2300 rating points) and found no significant increase in depth of search. However, international masters and grandmasters sometimes carry out shallower search than masters (Saariluoma, 1990a), perhaps indicating that they can tailor their search mechanisms to the demands of the position. Gobet (1997a) carried out computer simulations with the SEARCH model (see below) and concluded that average depth of search keeps increasing with higher skill levels, but with diminishing returns (i.e., it follows a power law).

<C>. *Selective Search, Move Generation, and Pattern Recognition*. De Groot found that all players were highly selective in their search, rarely visiting more than one hundred nodes before choosing a move. Recent results support this view. Calderwood et al. (1988) showed that masters can make relatively good decisions even under time pressure (about 5 s per move). Gobet and Simon (1996d) found that world champion Kasparov, when playing simultaneous games against teams consisting of up to eight international masters and grandmasters, performed at a level that still placed him in about the six best players in the world. Gobet and Simon argued that, while Kasparov's performance was weaker than in normal games and showed more variability, it was higher than theories mainly based on search would predict (but see Lassiter, 2000, and Chabris & Hearst, 2003 for opposing views). Comparing the quality of play of world-class grandmasters in standard games (about 3 minutes per move, on average) and rapid games (less than 30 seconds per move, on average), Chabris and Hearst (2003) found that this decrease of thinking time by a factor of six only marginally affected the number of blunders per 1,000 moves (5.02 in classical games vs. 6.85 in rapid games). While they took this as evidence for the role of search, a more natural interpretation of these results is that they show that a substantial decrease in thinking time fails to increase the number of blunders substantially, which counts as direct support for theories emphasising pattern recognition.

Proponents of search models often cite Holding and Reynolds' (1982) experiment as evidence that search and pattern recognition can be dissociated. Holding and Reynolds, who used semi-random positions as stimuli, first asked players to recall the position after an eight-second presentation, and then to choose what they thought would be the move. They found that skill correlated with the quality of chosen move after a few minutes' deliberation, but not with the recall or the evaluation after brief presentation. Schultetus and Charness (1999) extended Holding and Reynolds' (1982) experiment with a crucial addition: they asked players to recall the position at the end of problem solving. Like in the original study, stronger player did not recall the position better after 5 seconds, but chose better moves. However, they also obtained better results in the recall performance following problem solving. Schultetus and Charness (1999) argue that these results are consistent with the hypothesis that pattern recognition underpins skill in chess. That is, in order to choose better moves, better players were able to form new relational patterns for the unusual piece placements. These new chunks provided the recall advantage after problem solving. Such results are also consistent with the Ericsson and Kintsch (1995) long-term working memory perspective.

<C> Progressive Deepening. De Groot (1946) found that players were visiting the same branches of the search tree repeatedly, either directly or after visiting other branches. According to de Groot, this phenomenon of "progressive deepening" occurs both in order to compensate for limitations in memory and for propagating information from one branch of the search tree to another (De Groot, 1946; De Groot & Gobet, 1996). Gobet (1998b) found that skill affects how progressive deepening is

carried out. The maximum number of immediate re-investigations (where the same base move is analyzed directly in the next episode) was proportional to players' strength, while the maximum number of non-immediate re-investigations (where the analysis of a base move and its reinvestigation is interrupted by the analysis at least one different move) was inversely proportional to players' strength.

<C> High-Level Knowledge and Planning. De Groot (1946), who emphasized the role of conceptual knowledge in chess expertise, reported that players' descriptions of games were centred on key positions; this finding has been confirmed by recent research (e.g., Cooke et al., 1993; De Groot & Gobet, 1996; Saariluoma, 1995). The presence of these key positions enables masters to acquire what de Groot called a "system of playing methods", many of which are stereotypical. By applying this routine knowledge, masters can often find good moves with minimal look-ahead. Saariluoma (1990a, 1992) tested this hypothesis with tactical positions, and found that strong players tended to choose stereotyped solutions and missed shorter (but non-typical) solutions.

Saariluoma and Hohlfeld (1994) were interested in planning with strategic positions. They found that null moves (missing moves for one side) were common (about 12 per cent of all moves). This result is similar to the 10 per cent found in a previous study by Charness (1981a). In a second experiment, Saariluoma and Hohlfeld (1994) changed the nature of positions by relocating a key piece, so that a combination possible before the transformation could not be carried out after. Eliminating the combination produced an increase of the number of null moves.

<C> *Computational models of problem solving*. Simon and his colleagues developed a number of process models of problem solving in chess (Baylor & Simon, 1966; Newell & Simon, 1972), and two production systems at the boundary between cognitive science and artificial intelligence were written by Wilkins (1980) and Pitrat (1977). Gobet and Jansen (1994) describe a program that uses pure pattern recognition to select moves, without carrying out any search. This is presented more as a first step toward a full problem-solving program than as a theory of human problem solving. Gobet (1997a) describes SEARCH, a probabilistic model that integrates pattern recognition and search. This model, which is a direct implementation of the template theory and which incorporates insights from previous theories (e.g., De Groot, 1946; Newell & Simon, 1972), does not play chess but computes several measures such as depth of search, rate of search, and the level of fuzziness in the mind's eye as a function of the skill level (i.e., number of chunks).

When generating moves from the stimulus position or later during look ahead, the model uses either fast pattern recognition (chunks and templates) or slower heuristics. The same methods are used when the model evaluates positions at the end of a sequence of moves. The generation of an episode (sequence of moves) is stopped when the level of fuzziness in the mind's eye is too high, an evaluation has been proposed, or no move or sequence of moves has been proposed. It is assumed that information in the mind's eye decays at a constant rate, which interferes with search. Finally, the model has a time cost for every cognitive operation; for example, it takes 2 s to carry out a move in the mind's eye, and 10 s to evaluate a position using heuristics.

The program predicts that depth of search follows a power law of skill. When simulating a small number of participants (as is typical in chess research), the program also shows substantial variability, as was found in Saariluoma's (1992) study, where international masters and grandmasters searched less than weaker masters.

<B> Blindfold Chess.

A number of studies have investigated blindfold chess, to which Binet (1894) had already devoted a lengthy study. In blindfold chess, a player carries out one or several games without the view of the board and the pieces; the moves are communicated through standard chess notation.

Ericsson and Oliver (1984; cited in Ericsson & Staszewski, 1989) investigated the nature of the representation for chess positions dictated move by move with a player of near master strength. In a set of experiments they demonstrated that the retrieval structure utilized by the player was extremely flexible, permitting very fast responses about what piece was present (or if the square was unoccupied) to probes (square names in algebraic notation) of each square on the chessboard. In some cases the response time of about 2 s was faster than that obtained when the player looked at a chessboard position and was probed with the name of a square. They also found that when the player memorized two chess positions, responses to probes of the squares of the chessboard improved with successive tests from the same board at a much faster rate than in conditions where there were random probes or when probes alternated across boards. In further experiments they demonstrated that the representation structure was different for memory retrieval versus perceptually available retrieval conditions. Such flexibility in the encoded representation is necessary for being able to choose good moves when playing blindfolded. (See Gobet, 1998a, for a further discussion of these results.)

Saariluoma (1991) studied memory for move sequences using blindfold chess. He dictated one move every 2 s, from three types of sequences: moves actually played in a game, random but legal moves, and random and possibly illegal moves. He found that masters could recall almost perfectly the position for the moves taken from actual games and legal random moves after 15 moves, but performed poorly with illegal random moves. With additional moves, the recall of legal random moves decreased much faster than that of game moves. Saariluoma proposed that legal random moves initially allow for a relatively good recall because they only slowly produce positions where it is not possible to recognize chunks. These results are in line with Chase and Simon's (1973b), who studied memory for moves with plain view of the board.

In a series of experiments, Saariluoma (1991) and Saariluoma and Kalakoski (1997) systematically investigated memory for blindfold games. They presented one or several games aurally (dictating moves using the standard algebraic chess notation) or visually (presenting only the current move on a computer screen). Only a few of their results can be presented here: blindfold chess requires mainly visuo-spatial working memory, and makes little use of verbal working memory; differences in LTM knowledge (e.g., number of chunks) rather than differences in imagery ability underpin skill differences; abstract representations are essential (cf. also Binet's, 1894); and there is no difference between auditory and a visual presentation.

Campitelli and Gobet (2005) used blindfold chess to study how perception filters out relevant from irrelevant information. They found that irrelevant information affects chess masters only when it changes during the presentation of the target game.

Problem solving has also been studied using blindfold chess (Saariluoma & Kalakoski, 1998). In a task consisting in searching for the best move, they found that players memorized pieces better when these were functionally relevant. This difference disappeared in a task where players had to count the number of pieces. They also found that tactical combinations embedded in a game position were easier to solve than those contained in a random position. As with normal chess, visuo-spatial interfering tasks negatively affect problem solving performance. Finally, Chabris and Hearst (2003) found that the number of blunders did not increase much when grandmasters played blindfold games as compared to games with the view of the pieces.

Campitelli and Gobet (2005) argue that most of the results found on blindfold chess can be explained by the template theory.

<A> Building a Human Master

<B>Prodigies: Born or Made, and the Issue of Critical Periods.

In the last decade, psychology has seen renewed interest in the question of the roles of talent and practice, and the psychology of expertise is no exception. This section contains a brief review of topics related to this question that can be roughly classified in three headings: development, training and education, and neuroscience. A fair conclusion from the available evidence is that we do still not have data rich enough to determine how they might interact in the development of chess expertise.

<C> *Developmental Issues*. In a classic study on the role of knowledge on memory development, Chi (1978) found that, while non-chessplaying adults were better at memorizing digits than chess-playing children, they were worse at memorizing game positions. Thus, domain-specific knowledge can override developmental differences. Schneider et al. (1993) extended Chi's study by adding child novices and adult experts to the design; they also presented random positions and added a non-chess visuo-spatial control task. Adults and children offered the same pattern of results: experts' superiority was the largest with meaningful positions, was reduced with the random positions, and all but disappeared with the board control task (while absent in the first trial, skill effects were apparent in later trials).

<C> *Learning*. Several longitudinal studies have trained novices to memorize chess positions (Ericsson & Harris, 1990; Saariluoma & Laine, 2001; Gobet and Jackson, 2002). Typically, learning follows a power function. Computer models based on chunking could simulate the data relatively well (Saariluoma & Laine, 2001; Gobet & Jackson, 2002). A power function of learning was also found in Fisk and Lloyd (1988), who studied how novices learn the movement of pieces in a pseudo-chess environment.

Didierjean, Cauzinille-Marmèche and Savina (1999) were interested in how chess novices use reasoning by analogy in learning to solve chess combinations (smothered mates). The results show that transfer was limited to problems perceptually similar to the examples and did not extend to problems requiring the use of the abstract principle behind the solution of these problems.

<C> *Training and Education*. Given the importance of deliberate practice in an entrepreneurial domain such as chess, one could expect that powerful training methods have been developed. There is not much about this topic in the literature, however. Gobet and Jansen (in press) show how educational principles that can be used in chess training can be derived from the template theory. The necessity of having a coach is debated in the literature; for example, Charness, Krampe and Mayr (1996) found a bivariate but not a unique multivariate correlation between chess skill and the presence of a coach in one sample; however, Charness, Tuffiash, Krampe, Reingold and Vasyukova (2005) did find it in another. Gobet, Campitelli and Waters (2002) note that using computer databases and playing computers may provide more efficient training tools than traditional training practice based on books, which is consistent with the progressive replacement of the latter by the former in professional practice. This change in training practice techniques may well explain Howard's (1999) observation that the number of young players among the world's elite has increased in the last decades, which he takes as evidence that average human intelligence is rising overall. Another explanation is that as young player populations increase, the best-trained individuals should reach higher levels of performance (Charness & Gerchak, 1996).

Do skills acquired in playing chess transfer to other domains? Gobet and Campitelli (in press) reviewed all the available publications. Most studies did not meet criteria of robust scientific research, but two well-controlled studies (Frank & d'Hondt, 1979; Christiaen & Verhofstadt-Denève, 1981) found that a chess-playing group outperformed a control group in verbal ability and school results, respectively. A limit of these 2 studies is that a large number of tests was used, which raises the possibility of type I errors.

<C> *Individual Differences*. Data about individual differences do not offer a clear pattern. There is evidence that chess skill correlates with measures of intelligence, both in children (Frank & d'Hondt, 1979; Frydman & Lynn, 1992; Horgan & Morgan, 1990) and adults (Doll & Mayr, 1987). However, while Frank and d'Hondt (1979) and Schneider, Gruber, Gold and Opwis (1993) found that chess experts perform better than control in non-chess visuo-spatial tasks with children and teenagers, Djakow, Petrowski, and Rudik (1927), Doll and Mayr (1987) and Waters, Gobet and Leyden (2002) failed to find such differences with adults. Note that all the above studies, with the exception of Frank and d'Hondt (1979) who had an experimental design, used quasi-experimental designs; therefore, the results are based on correlations, which are equivocal about the direction of causality (is intelligence a prerequisite to chess skill, or does chess playing improves one's intelligence?). The differing patterns between children and adults are consistent with developmental theories that propose differentiation of abilities across time. Early in development all forms of problem solving are dependent on fluid intelligence (search) but later, crystallized intelligence (knowledge: templates and chunks) changes the way that problem solving is carried out.

<C> *Neuroscience.* Based on the responses to a questionnaire sent to players rated in the US Chess Federation ranking list, Cranberg and Albert (1988) found that 18% of male chess players were not right-handers. This percentage is reliably higher than that in the general population (~11%).

Chabris and Hamilton (1992) carried out a divided visual-field experiment with male chess players, and found that the right hemisphere was better than the left at parsing patterns according to the default rules of chess chunking, but that the left hemisphere was more efficient at grouping pieces together when these rules did not apply.

Several brain-imaging techniques have been employed to study chess skill (Atherton et al., 2003; Campitelli, 2003; Nichelli et al.; 1994; Onofrj et al., 1995; Amidzic et al., 2001). Overall, these studies suggest that frontal and posterior parietal areas, among other areas, are engaged in chess playing. These areas are known to be engaged in tasks requiring working-memory processes. There is also some evidence that chunks are encoded in temporal lobe areas, including the fusiform gyrus, parahippocampal gyrus and inferior temporal gyrus. In a different line of research, Campitelli (2003) found that the left supramarginal gyrus and left frontal areas were involved in autobiographical memory in two chess masters.

<B> *The Role of Deliberate Practice and Tournament Experience.*

As appears to be true in other domains (see other chapters in this volume) skill acquisition in chess requires a considerable investment. Few players reach master level performance with less than 1000 hours of serious study (Charness, Krampe &

Mayr, 1996). Relying on responses to retrospective questionnaires, these investigators probed a large sample of tournament players from different countries focusing on how much time they spent in serious study alone (deliberate practice) versus that spent in tournament play and analysis of games with others. Other predictors for current skill level included variables such as current age, starting age, age when serious about chess, age when joining a chess club, presence of coaching, and size of chess library. The variables making independent contributions to explaining current chess rating were serious study alone, size of chess library, and current age. Tournament play was not statistically significant after taking deliberate practice time into account.

Not surprisingly, age was a negative predictor (older players tended to have lower ratings, averaging a loss of about 5-6 rating points per year), whereas deliberate practice and size of chess library were strong positive predictors, accounting in combination for nearly 70 percent of explained variance in current rating.

In an enlarged version of the first sample and in a new sample, Charness, Tuffiash, Krampe, Reingold and Vasyukova (2005) showed a somewhat different pattern of relationships, with both coaching and tournament play in addition to deliberate practice making independent predictions to current chess rating. For predicting a player’s peak rating, the two practice variables accounted for most of the variance. Of course, this correlates approach suffers from the weakness that causality is not identifiable. Longitudinal research is needed to trace out how process variables covary with changes in rating.

<A> Conclusion

The combination of empirical and theoretical work has identified and successfully characterized a rich range of phenomena from cortical activation patterns to eye movement patterns and from memory for static chess positions to memory for sequences of moves (including blindfold chess). Many phenomena identified are central to the concerns of psychology, particularly to theories about individual differences, memory systems, developmental processes, and theories in cognitive science. The discovery of the strong relation between skilled perception processes and skilled problem solving has influenced theory development in many other domains. For instance, chess research has been useful in characterizing the tradeoffs seen between memory, perception, and problem solving performance, as well as in assessing the role of deliberate practice in maintaining performance across the life span (Krampe & Charness, this volume). Simulation work has proven useful in describing how aging processes interact with knowledge processes to predict memory performance (Mireles & Charness, 2002).

Nonetheless, many issues remain unresolved. It is not yet clear how deliberate practice and cognitive abilities jointly determine performance across the life span given the differing patterns seen in children, young adults, and older adults. Tighter links still need to be drawn between perceptual processes and search processes, particularly as a function of skill level. With the ready availability of modern tools (neuro-imaging, eye tracking, simulation) in conjunction with reliable older ones (think-aloud protocol analysis), the future seems bright indeed for expanding our knowledge of expertise in chess.

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