MEMORY IN CHESS PLAYERS: COMPARISON OF FOUR THEORIES

FERNAND GOBET
ESRC Centre for Research in Development, Instruction and Training
Department of Psychology, University of Nottingham
University Park, Nottingham NG7 2RD
United Kingdom
email: frg@psyc.nott.ac.uk

ESRC Centre for Research in Development, Instruction and Training
August 1996
Technical Report No. 43

Abstract

This paper compares four current theories of expert memory with respect to chess players' memory: Chase and Simon's (1973) chunking theory, theories stressing the role of conceptual knowledge and levels of encoding, Ericsson and Kintsch's (1995) long-term working memory, and Gobet and Simon's (in press-b) template theory. It is shown that the template theory outperforms its rivals in accounting for the empirical evidence. The theory, which unifies low-level aspects of cognition, such as chunks, with high-level aspects, such as schematic knowledge and planning, suggests that chunks are accessed through a discrimination net, and that they can evolve into more complex data structures (templates) specific to classes of positions.

Email: frg@psychology.nottingham.ac.uk
Phone (0115) 951 5402, Fax (0115) 951 5324

CONTENTS

1. ADVANTAGES OF CHESS AS A RESEARCH DOMAIN 3
2. TWO HARBINGER THEORIES 4
2.1 BINET: SEARCHING FOR VISUAL IMAGES 4
2.2 DE GROOT: SETTING UP THE RESEARCH AGENDA 5
3. CURRENT THEORIES OF EXPERT MEMORY IN CHESS 6
3.1 CHASE AND SIMON'S CHUNKING THEORY 6
3.2 KNOWLEDGE-BASED THEORIES 7
3.3 SKILLED MEMORY AND LONG-TERM WORKING MEMORY THEORIES 7
3.4 TEMPLATE THEORY 8
4. REVIEW OF EMPIRICAL EVIDENCE 10
4.1 EVIDENCE FOR SKILL DIFFERENCES IN EARLY PERCEPTION 10
4.2 STM CAPACITY AND LTM ENCODING 11
4.2.1 Interference Studies 11
4.2.2 Random Position 13
4.2.2.1 Recall experiments. 13
4.2.2.2 Recognition experiments. 14
4.2.2.3 Theoretical implications. 14
4.2.3 Number of Pieces 14
4.2.4 Recall of Games 15
4.3 MODALITY OF REPRESENTATION 16
4.4 LTM ORGANIZATION 18
4.4.1 Evidence for Chunks 18
4.4.2 Number of Chunks in LTM 19
4.4.3 Hierarchical Organization 20
4.4.4 Conceptual Representation 21
4.4.4.1 Typicality. 21
4.4.4.2 Effect of semantic orientation. 22
4.4.4.3 Theoretical implications. 23
4.4.5 Direct Evidence for Retrieval structures 23
4.5 LEARNING 24
4.5.1 Short-Range Learning 24
4.5.2 Medium-Range Learning 26
4.5.3 Long-Range Learning 26
4.6 PROBLEM SOLVING 27
5. DISCUSSION 28
6. REFERENCES 31

Memory in Chess Players: Comparison of Four Theories

Understanding what makes experts so good in their domain of expertise is a traditional field of psychology, which goes back at least to Binet's (1894) monograph on the psychology of skilled mental calculators and chessplayers. Recently, cognitive science and cognitive psychology have produced a wealth of empirical data, and several theoretical explanations of expertise have been proposed. In particular, research on expert memory has been flourishing, gathering a large amount of data, which have sufficient power to test current theories. It is then a good time to compare some of the main contenders.

With this goal in mind, two main approaches are possible: to compare theories across several domains, emphasizing the general principles stressed by each theory, or to focus on a particular domain, analyzing in detail the explanations offered by each theory. The latter approach has been chosen in this paper, perhaps to counterbalance the rather strong tendency within the field to offer general, but sometimes vague, explanatory frameworks. The domain of chess was selected, for several reasons: first, it has a long tradition in scientific psychology; second, it is probably one of the domains of expertise offering the richest database of empirical data; and third, several detailed theories, implemented as computer programs, have been developed to account for various aspects of chess players' memory and perception.

The first section of this paper emphasizes the scientific advantages offered by the study of chess players. The second section summarizes two classical contributions to the study of expert memory that helped shape the field, each in a different way. Binet (1894, 1966) showed that knowledge held in memory plays a crucial role in chess expertise. De Groot (1946/1978) devised a very efficient procedure to explore this memory empirically. The third section introduces four theoretical approaches that have recently been applied to expert memory in general and chess memory in particular: Chase and Simon's (1973b) chunking theory; Ericsson and Kintsch's (1995) long-term working memory; Gobet and Simon's (in press) template theory; and, finally, a composite framework, which I will call knowledge-based theories, and which has been often offered as an improvement over Chase and Simon's (1973b) model. The theories belonging to the latter framework stress the role of high-level, conceptual knowledge, sometimes referring to the levels-of-processing theory (Craik & Lockhart, 1972). These four approaches will be compared with respect to empirical work done during the last twenty years or so on chess memory. In the conclusion, the respective explanatory power of these theories will be discussed, both within and outside chess memory.

The reader who has come across several reviews of chess expertise in the recent years (e.g., Charness, 1989, 1992; Cranberg & Albert, 1988; Holding, 1985, 1992; Lories, 1984) may wonder why a new theoretical article should be written on this topic. There are two main reasons. First, several theoretically important empirical results have been published recently (Cooke, Atlas, Lane, & Berger, 1993; De Groot & Gobet, in press; Gobet & Simon, in press-b, in press-c; Saariluoma, 1994, 1992), as well as a rebuttal of a widely cited result about the lack of skill effect in the recall of random positions (Gobet & Simon, in press-d). Second, two new theories (Ericsson & Kintsch, 1995; Gobet & Simon, in press-b) have been proposed recently to address deficiencies of the classical Chase and Simon theory. No previous review has systematically put these two theories (as well as others) to the trial of empirical data.

1. ADVANTAGES OF CHESS AS A RESEARCH DOMAIN

Before getting into the substance of this paper, it may be useful to discuss the advantages offered by chess as the domain of comparison of the four theories, and how the conclusions this comparison will yield may be generalized to other domains. Historically, chess has been one of the main sources of the scientific study of expertise, a rapidly developing field of cognitive psychology. Its impact on cognitive psychology in general is important (Charness, 1992) for several reasons (see Gobet, 1993a, for a more detailed discussion): (a) the chess domain offers a strong external validity; (b) it also offers a strong ecological validity; (c) it is a complex task, requiring several years of training to reach professional level; (d) it offers a rich database of games played by competitors of different skill levels which may be used to study the chess environment statistically; (e) it is a relatively “clean” domain which is easily formalizable mathematically or with computer languages; (f) its flexible environment allows many experimental manipulations; (g) it allows for a cross-fertilization with artificial intelligence; (h) it offers a precise scale quantifying players’ expertise (the ELO rating;[1] see Elo, 1978); and finally, (i) it permits the study of cognitive processes both at a low level (e.g., reaction time to detect the presence of pieces on the board) and at a high level (e.g., choice of a move after several minutes of deliberation), providing valuable data for the cognitive study of both basic processes and high-level aspects of expertise. As an example of the first point mentioned, external validity of the chess domain, note that the basic result of De Groot (1946/1978) and Chase and Simon (1973a, 1973b)—experts’ superiority over novices with meaningful material in their domain of expertise—has been replicated with different domains, such as chess problems[2] (Kovacevic, 1985, cited by Gruber & Strube, 1989), GO and gomuku (Eisenstadt & Kareev, 1977; Reitman, 1976); bridge (Engle & Bukstel, 1978; Charness, 1979); music (Sloboda, 1976); electronics (Egan & Schwartz, 1979); programming (Shneiderman, 1976; McKeithen, Reitman, Rueter & Hirtle, 1981); and basketball (Allard, Graham & Paarsalu, 1980).

2. TWO HARBINGER THEORIES

A presentation of the historical roots of research on chess skill will help understand the current theoretical concerns about chess memory. In this section, the works of Binet and of De Groot are discussed, with special emphasis on the questions that will recur later in the comparison of the four candidate theories.

2.1 Binet: Searching for Visual Images

The first scientific study of chess memory was carried out by Alfred Binet (1894, 1966). Binet was intrigued by one of the most spectacular and strenuous forms of chess—blindfold chess. In this variant of chess, a player carries out one (or several) game(s) without seeing the board and the pieces (moves are indicated using standard chess notation). Binet’s first intention was to study the role of visual images, his a priori hypothesis being that chess players use a visual, concrete representation of the board and of the pieces. Upon the analysis of the questionnaires he had sent to the best players of the time, Binet had to reverse his position. He concluded that blindfold chessplayers’ representation is very abstract and does not rely upon a detailed visualization of the pieces and the board. By the conclusion of his book, Binet had switched the burden of this theoretical explanations from visualization to memory. He proposed that blindfold chess requires three essential abilities: erudition, imagination and memory.[3]

Erudition is acquired through the study of chess literature and by playing games. It constitutes a specific knowledge that gives a meaningful context into which individual moves may be integrated. Binet distinguishes this memory of ideas, or schematic memory, from memory of sensations, which is related to sensorial images. Imagination characterizes the ability to visualize a position. Contrary to Binet’s expectations, strong players did not much use such a concrete visual memory. Although they did have the feeling of seeing a board with pieces, board limits were fuzzy, and the pieces had uncertain shapes and blurry colors. It seems that uncritical features, such as color or shape of the pieces, are abstracted for economy’s sake, so that players can concentrate on relevant elements. Memory is divided by Binet into visual memory (or memory of position, cf.

imagination), memory of touch, and verbal memory (or recapitulation memory). Whereas the second type of memory does not seem to play any role in blindfold chess, the third one, which consists of a "mental repetition of pronounced words," is useful in three ways. It allows the expression of reasoning and of search, the reconstruction of the visual image of the position using the verbal memory of the moves, and finally the recognition of the color of squares by some mnemonic tricks.

It is clear from his book that Binet had the feeling of being stuck at an impasse. The master of psychological measurement did not find an adequate tool to quantify chess memory and visualization, a feat he achieved at a very high level in the other part of his 1894 book, in which he measured with precision the abilities of skilled mental calculators with techniques that are still in use now in this field of research (see Staszewski, 1988).

2.2 De Groot: Setting Up the Research Agenda

If we set aside the contributions of Cleveland (1907) and Djakow, Petrowski and Rudik (1927), who were interested in the development of expertise and in the general intellectual capacities in chess players, respectively, the next important contribution to the study of chess memory was De Groot's thesis (1946/1978). De Groot's effort was mainly devoted to a qualitative description of the processes chess players carry out to choose a move during a game. However, his work is best known both for his quantitative results showing no difference between players of various strengths in the macrostructure of search (depth of search, number of nodes, branching factor...) and also for his demonstration that level of chess skill affects dramatically the recall of positions shown for a short amount of time.

De Groot's memory experiment, which sets up the program of much experimental work, is simple. A chess position, taken from a master game unknown to the subjects, is presented to them for a short amount of time (De Groot varied the time from 2 to 15 seconds). The chess position is then removed from their sight, and they have to reconstruct it on a different board. The number of pieces correctly placed, or some similar measure, gives an index of subjects' memory performance.

De Groot's results were dramatic: his grandmaster[4] remembered the position almost perfectly after a presentation ranging from 2 to 5 seconds (an average of 93% pieces correct), while his weakest subject, the equivalent of a class A player, barely got 50% correct. Moreover, strong players' protocols show that they grasp rapidly the meaning of the positions after a few seconds, understanding the main strategic features and literally seeing, if not the best move, then at least a reasonably good move (De Groot, 1978, De Groot & Gobet, in press).

According to De Groot, chess masters do not encode the position as isolated pieces, but as large, mostly dynamic "complexes." These complexes are generally made of pieces but may sometimes incorporate some empty squares that play an important role in the position. Masters' perception of a position as large units and their ability to rapidly zero in on the core of the position are made possible by the knowledge they have gathered during their study and practice of the game. De Groot has later shown (De Groot, 1966, De Groot & Jongman, 1966; De Groot & Gobet, in press) that masters' superiority is not provided by a general knowledge of first-order probabilities of piece locations on the board, but by a very specific type of knowledge that is actualized during the recognition of typical formations.

For De Groot, the necessary knowledge to reach mastership include (a) a highly specific and developed perception mode, and (b) a system of reproductively available methods stored in memory. Two types of knowledge are distinguished: knowledge (knowing that...) and intuitive experience (knowing how...). The first may be verbalized, but not the second. De Groot was mainly interested in the content of these types of knowledge and did not go into the question of how they are implemented in human memory.

3. CURRENT THEORIES OF EXPERT MEMORY IN CHESS

This section presents four current theories (or groups of theories) that have been proposed to account for expert memory in general and chessplayers' memory in particular. Each theory will be illustrated by giving its explanation for the standard memory task (recall of a game position presented for 5 seconds).

3.1 Chase and Simon's Chunking Theory

Chase and Simon (1973a) re-investigated De Groot's (1946/1978) recall experiment, adding both methodological and theoretical contributions. Studying the latencies between the placement of pieces during a copy and a recall task, they found that their master recalled bigger chunks (Miller, 1956), as well as more chunks. As an explanation of their master's performance, they proposed that he had stored a large number of patterns in long-term memory (LTM), such as typical pawn castle formation, pawn chains, common constellations on the first rank, and typical attacking configurations. A statistical analysis showed that more than half of these constellations are pawn structures, which constitute a relatively stable feature of the position.

Simon and Gilmartin (1973) describe a computer program that implemented a subset of the chunking theory and simulated the memory processes of chess players. This program—named MAPP (Memory Aid Pattern Perceiver)—combined elements of PERCEIVER (Simon & Barenfeld, 1969) and of EPAM (Elementary Perceiver and Memorizer), a model of LTM learning (Feigenbaum & Simon, 1962; Feigenbaum, 1963; Feigenbaum & Simon, 1984; Richman & Simon, 1989). Their model proposed that a discrimination net functions as an LTM index which allows the identification of piece configurations, and that chess players, once a configuration has been identified, place a pointer to it into short-term memory (STM). The model implemented STM as encoding a set of patterns without semantic or ordered relation each other. In essence, this theory proposed that masters' skill is based on their stock of configurations in LTM, which allows them, during a memory task, to recognize known patterns. An important aspect of the theory was that the same cognitive limitations (e.g., STM capacity, encoding rate into LTM) apply in chess memory as in other cognitive domains.

When used as simulated subject, MAPP produced results that were quantitatively inferior to masters' results, but superior to class A players' results. Qualitatively, MAPP placed the same groups of pieces as human players. Extrapolating from these results, Simon and Gilmartin (1973) estimated that grandmasters' results may be explained by a repertoire ranging from 10,000 to 100,000 configurations (the estimate of 50,000 is often found in the literature). Simon and Chase (1973) noted that a similar number of words belong to the vocabulary of a competent English speaker, and that such a quantity of patterns requires at least ten years of learning.

Continuing their theoretical investigation, Chase and Simon (1973b) proposed the model of the "mind's eye," which extends the chunking theory to account for problem-solving behavior. Mechanisms that underlie chess expertise are, according to these authors, more visuo-perceptive than logico-deductive. Chess expertise consists of players' ability to perceive almost automatically the good moves in a given position. Chunks are represented in LTM by an internal name associated with a set of instructions that permit the patterns to be reconstituted as an internal image in the mind's eye. The mind's eye consists of a system that stores perceptual structures, both from external inputs and from memory stores, and that can be subjected to visuo-spatial mental operations. It contains relational structures, and new information can be abstracted from it.

Chunks contain information about plausible moves. Thus, LTM chess chunks are activated by the constellations on the external chessboard and trigger potential moves that will then be placed into STM for further examination. The choice of a move, then, depends both on a selective search in the space of the legal possibilities and on pattern recognition. The mind's-eye model acts as a production system (Newell & Simon, 1972); each familiar chunk in LTM is both a condition that may be satisfied by the recognition of the pattern on the board, and an action that evokes a move associated to this pattern.

Although Chase and Simon's approach shares some features with De Groot's—in particular the stress on perceptual processes—some differences need to be noted. Chase and Simon view perception as a passive process, while De Groot emphasizes the dynamic component of it. For him, perception is problem solving (De Groot & Gobet, in press).

3.2 Knowledge-Based Theories

In discussing the (sometimes presumed) weaknesses of the chunking theory, several authors have localized experts' superiority in qualitative differences in their knowledge organization. The theories belonging to this composite—and rather heterogeneous—framework share one common feature: they assume that information about the environment can be stored using characteristics going from concrete (shallow, local) to abstract (deep, global), and that skilled individuals use generally abstract (deep, global) encoding while less skilled individuals use concrete (shallow, local) encoding.

Several knowledge-based explanations have been proposed. De Groot (1946/1978) mentioned several aspects (knowledge complexes; declarative vs. procedural knowledge) which may be included to this general approach. Later, Hartston and Wason (1983) suggested that masters do not reconstruct the position ab initio but see unconsciously this position as a corrected version of a prototype. Lories (1984) stressed that, after a perceptive phase during which independent units are produced, a categorization phase is taking place, which takes into account the global characteristics of the position and which actively assists encoding. In Lories's view, the material is not simply stocked in STM as chunks, as proposed by Chase and Simon's (1973b) model, but is processed through LTM information. Others (e.g., Lane & Robertson, 1979; Goldin, 1978b) have proposed to apply to chess Craik and Lockhart's (1972) model of levels of processing. From this viewpoint, strong players recall a game position better than weak players because they can access deeper semantic codes, offering more encoding opportunities and, therefore, redundancy. Finally, Pfau and Murphy (1988), as well as Cooke et al. (1994) have stressed the role of verbal high-level knowledge: in their view, players access a high-level, prototypical description of the position during a recall task, which characterizes the position at a much higher level than that of chunks (4-5 pieces). Finally, Holding's (1985) SEEK (SEarch, Evaluate, and Know) theory stresses that strong players possess rich and highly organized knowledge of specific openings or types of positions as well as of general principles. These principles are crucial in acquiring expertise, and most of them are encoded verbally. For Holding, ability to recall a game position after a brief exposure is a by-product of strong players' familiarity with it. Familiarity with the position allows a player to classify it as a "set of interlocking common themes, or as a set of deviations from prototypes in LTM, while committing very little to rote memory" (Holding, 1985, p. 249).

Although the theories belonging to this composite framework are often mentioned to account for chess memory, they have never been clearly systematized, let alone systematically subjected to empirical evidence. In particular, no detailed mechanisms have been proposed to refine them into workable models. As will be seen later, it is often impossible to use these theories without adding numerous ad hoc hypotheses.

3.3 Skilled Memory and Long-Term Working Memory Theories

The skilled memory theory (Chase & Ericsson, 1982; Staszewski, 1990; Ericsson & Staszewski, 1989), explains experts' remarkable memory in various domains through three principles: (a) Information is encoded with numerous and elaborated cues related to prior knowledge; (b) Retrieval structures (pre-learned LTM structures that contain domain-specific slots and, therefore, allow a rapid encoding into LTM) are developed; and (c) Time required by encoding and retrieval operations decreases with practice. This approach has been applied mainly to mnemonists, though it has also be applied to some skills where memory develops as a side-product, such as mental calculation. A good example of such a retrieval structure is offered by the method of loci, in which one learns a general encoding scheme using various locations. During the presentation of material to learn, associations are made between the locations (the "slots") and the items to learn. An important aspect of this theory is that experts must activate their retrieval structure before the material is presented, and that, in the case of very rapid presentation of items (e.g., one second per item) the structure can be applied successfully to encode only one type of material (e.g., digits) without transfer to other material. In summary, the development of expert memory includes both creating a retrieval structure and learning to use it efficiently.

Recently, Ericsson and Kintsch (1995) have developed a more general variant of the skilled memory theory, which they name "long-term working memory." They propose that cognitive processes occur as a sequence of stable states representing end products of processing, and that acquired memory skills allow these end products to be stored in LTM. Encoding occurs either through a retrieval structure, or through a knowledge-based, elaborated structure associating items to other items or to the context (schemas and other patterns in LTM), or both. The former type of encoding predicts that, due to the presence of retrieval cues, a relatively good recall should be observed even when no schema is accessed.

In the case of chess expertise, the long-term working memory theory proposes that strong players use a retrieval structure representing the 64 squares of the board, which allows them to encode individual pieces and to represent a position as an integrated hierarchical structure (Ericsson & Kintsch, 1995; Ericsson & Staszewski, 1989). This structure, which both relates pieces each other and associates pieces to their corresponding locations, allows a rapid encoding into LTM. Interestingly, Gobet (1993a, 1993b) and Richman, Simon and Gobet (1991) have proposed a similar type of retrieval structure for chess but later reached (Gobet & Simon, in press-b) the conclusion that it was inadequate. Their reasons will be discussed later in this paper.

The chess memory evidence reviewed by Ericsson and Kintsch (1995, p. 237-8) addresses mainly experiments with rather long presentation times, but it is assumed that the retrieval structure is also used with success with short presentation times, as in the standard five-second presentation of a game position (Ericsson & Staszewski, 1989). Note that chess differs from the other tasks discussed by Ericsson and Kintsch (1995) in that individual units of information (in the case of chess, pieces) are assumed to be encoded into the retrieval structures very fast, on the order of about 160 msec (5 s divided by 32, since the retrieval structure can encode an entire position of 32 pieces), while all other experts discussed by

Ericsson require at least one second to encode one unit of information (such as digits with the subject studied by Chase & Ericsson, 1982, or menu orders with the subject studied by Ericsson & Polson, 1988). Unfortunately, Ericsson and Staszewski do not discuss these differences in encoding times.

3.4 Template Theory

As will be shown later, MAPP, as well as other models of the EPAM family, was strong in its ability to explain (chess) perception and memory at the chunk level, but weak in relating these chunks to high-level descriptions, partly because its main interests were on the index on LTM, and not on its semantic component (cf. Simon, 1976). As seen before, these high-level descriptions abound in masters' retrospective protocols (see for example De Groot, 1946/1978; De Groot & Gobet, in press) and may help explain how, upon recognition of a position, strong chess players access rapidly a network of knowledge allowing them to understand the subtleties of the position and to rapidly propose plausible moves and plans. Connecting low-level to high-level knowledge was an important motivation in developing the template theory (Gobet & Simon, in press-b) and was reached by combining the concept of chunk with that of retrieval structure.

The template theory is implemented as a computer program in the latest version of CHREST (Gobet, Richman & Simon, in preparation). Earlier versions of CHREST (Gobet, 1993a, 1993b) were developed to unify previous computer models of chess memory and perception (PERCEIVER, Simon and Barenfeld, 1969; MAPP, Simon and Gilmartin, 1973) with the idea of retrieval structure. An extension of the model embodies a production system that proposes moves after having recognized a pattern (Gobet & Jansen, 1994).

The perceptual part of the template theory remains basically the same as in MAPP: it is assumed that, when perceiving a chess board, chess players access chunks in LTM by filtering information through a discrimination net. Pointers to chunks in LTM are placed into STM, and rapidly-decaying visuo-spatial structures based on chunks are built up in the internal representation (cf. Chase & Simon's mind's eye). In the case of atypical positions, these chunks contain no more than the pieces that the system has recognized. In the case of typical positions, however, the discriminated node will give access to semantic memory, leading to information such as the opening the position may come from, which players are likely to reach this type of position, the plans and moves to apply, and so on. This information is organized in a schematic form (Larkin & Simon, 1987). For positions that subjects have studied or played extensively, it is proposed that chunks are developed into templates (see Gobet et al., in preparation, for the detail of the mechanism of template construction).

In contrast with the retrieval structures postulated by Chase, Ericsson, and Staszewski, which are general structures to be applied, within the domain of expertise, independently of the particularities of the material to be encoded, templates are specific to certain types of chess positions, and are not unlike prototypes. They offer, on the one hand, slots that are already instantiated and that form the core of the position. On the other hand, some slots may be filled in when viewing the position, in particular for features that are not stable in these types of positions. The slots of this second category may contain default-values, which are used when players have no time to focus on certain parts of the board. Slots may contain information on the location of certain pieces, on potential moves to play, or on any semantic information like plans, tactical and strategic features, and so on... The theory proposes that chunks and templates are mainly accessed by visual information, although other routes to them exist, allowing a high redundancy to memory: chunks and templates may be accessed by contextual cues, by description of strategic or tactical features, by the moves leading to the position, by the name of the opening the position comes from, or by the names of players known to often employ such type of position. As is the case with chunks of pieces, these routes may be modeled as discrimination nets. This redundancy may be useful for difficult tasks. For example, during recall experiments, the use of verbal description (e.g., strong players spontaneously try to associate the position with the name of an opening) may complement visual encoding. Note also that the presence of templates makes STM a more dynamic store than in MAPP: when new squares and new chunks are perceived, the model tries both to incorporate this new information into the template (if any), and to get a richer template through further discrimination.

Like the chunking theory, the template theory claims that expertise is due to: (a) a large database of chunks, indexed by a discrimination net; (b) a large knowledge base, encoded as production and schemas; and (c) a coupling of the (perceptual) chunks in the index to the knowledge base. In addition, it proposes that some nodes evolve into more complex data structures (templates) and that nodes in the discrimination net may be accessed through several paths, thus adding redundancy to the system. Construction of networks having the characteristics mentioned under (a), (b) and (c) explains why expertise in knowledge-rich domains takes such a long time to develop: in addition to learning chunks, which was emphasized in Chase and Simon's (1973a; 1973b) and in Simon and Gilmartin's (1973) papers, schemas and productions have to be learned, as well as pointers linking them together and linking them to chunks.

4. REVIEW OF EMPIRICAL EVIDENCE

Review of recent work in chess memory will focus on data directly relevant to the comparison of the four theories (see Gobet, 1993a, or Holding, 1985, for additional data on chess memory) and will be organized around the following themes: early perception, STM capacity and LTM encoding, modality of representation, LTM organization, learning, and problem solving.

4.1 Evidence for Skill Differences in Early Perception

Evidence suggesting that players of various skill levels differ at an early stage of perception would provide confirming evidence for the chunking and template theories, which both incorporate detailed perceptual mechanisms. As will be argued later, this evidence could also suggest limitations of the concepts of level of processing, high-level knowledge, and retrieval structure to their explanatory power of chess memory.

Studying eye movements, De Groot and Gobet (in press) show that there are clear skill differences in the way players look at a position: Masters' fixations are shorter, show less variance, cover more of the board, and cover more important squares than novices' fixations. In addition, masters fixate more often on the edges of the squares than the novices, which can be taken as evidence that they fixate group of pieces instead of individual pieces. Charness and Reingold (1992) also report similar differences in the case where only one quadrant of the board is presented.

Another crucial piece of evidence, likely to give indications on the automaticity of processes, is offered by subjects' performance when presentation times are very short. Ellis (1973) found that chess memory and chess skill correlate even with presentation times as short as 150 msec. Ellis used 4 x 4 square miniature chess boards and presented only common patterns of white pieces (white pieces on the first 4 ranks of a normal chess board, left or right side). His stronger subjects (class A players) were able to retain an average 6.7 pieces out of 8, and his weaker subjects (class D and below), 4.5 pieces. These results speak in favor of perceptual mechanisms independent of conscious control. Short presentation of entire boards yields similar results. For example, Gobet and Simon's (1995a) masters placed correctly about 70% of the pieces of a game position (a total of 26 pieces) after having seen the position for just one second and had close to 90% correct recall after a presentation of only two seconds. In addition, subjects sometimes recognize types of positions even with these short presentation times.

These results add support to the chunking and the template theories. Both predict that access to chunks and templates should be automatic, without recourse to any conscious process, and, therefore, present even with very short presentation times. In addition, a version of CHREST[5] (De Groot and Gobet, in press) was able to simulate in considerable details human eye movements. In addition to chunking mechanisms, the model implemented perceptual strategies, such as looking first at perceptually salient pieces.

Although the eye-movement studies fall outside the scope of the two other groups of theories, the data on short presentation times have some important theoretical implications for these theories. First, they indicate the need to explain how high-level knowledge is rapidly accessed through visual stimuli. Second, they show some inadequacies of the level-of-processing account: with a presentation time of one second, and in particular with the presentation time of 150 msec used by Ellis (1973), it is doubtful that subjects process the visual stimuli at different "levels." Hence, there are vast memory differences although players of different skill levels use the same level of processing. Finally, these results also show insufficiencies in the long-term working memory hypothesis (that a structure isomorphic to the chess board acts as a retrieval structure), because there is just not enough time, in these experiments, to encode information into this structure or to associate information with long-term schemas. The current retrieval structure theory could be salvaged in three ways: (a) by adding an alternative, as yet unspecified, route to schemas that offer a faster access than the route offered by retrieval structure cues (as indicated in Figure 4 of Ericsson and Kintsch, 1995); (b) by assuming that chunks and not individual pieces are encoded into the structure; and (c) by assuming that retrieval cues are activated during the (short) presentation time, even if these cues do not belong to a retrieval structure.

4.2 STM Capacity and LTM Encoding

4.2.1 Interference Studies

Empirical research has uncovered several weaknesses in the way Chase and Simon's (1973b) theory handles STM and LTM storage. In the case of the "classical" chess memory recall setting (presentation of a position for 5 s), Chase and Simon's theory clearly predicts that, since information is temporarily stored in STM and since the presentation time is not sufficient for LTM encoding, storage of additional stimuli following a chess position should wipe it out from STM. However, this is hardly the case. The most compelling result was found by Charness (1976), who used a variation of the Brown and Peterson paradigm (Brown, 1958; Peterson & Peterson, 1959). He inserted a delay of 30 s between the presentation and the recall of a chess position, with or without instructions to rehearse and either occupied or not by an interfering task.[6] Following such interference, there was an increase of latency time of the first piece to be reported, but the overall performance decreased only by 6 to 8%, little loss in comparison with experiments using the same technique with different material (nonsense trigrams). Interestingly, even interference due to chess material (such as finding the best move or naming the pieces in a different position) did not produce a significant degradation of performance. However, such material did produce a proactive interference effect, performance deteriorating from the first to the second half of the experiment. There was no such proactive interference effect in the case where simple recall (without intervening chess material) was requested. Charness proposed that redundant use of chess material provokes difficulties in the retrieval of information.

Charness's (1976) result throws doubt on an explanation based on a simple model that short term memory consists of a list of slots. Similar conclusions were reached by Frey and Adesman (1976), who used a different interfering task. Their subjects were confronted with two positions, presented in sequence for 8 s each, after which they had to count backward and aloud for 3 or 30 s. Finally, they had to reconstruct the first or the second position, without knowledge of which one was going to be chosen. Results indicated only a small loss of performance in comparison to a control condition where only one board was presented.

It seems to me that the interpretation of these results is more complicated than proposed by Frey and Adesman. If one takes into consideration the encoding time per chunk (from 5 to 10 s for meaningless material, according to Newell and Simon, 1972), and the relatively long presentation time (8 s) used in this experiment, Chase and Simon's (1973b) and Simon and Gilmartin's (1973) model accounts for the results. A little arithmetic establishes this: assuming that the 2 largest chunks (say 3 pieces each) are encoded into LTM, and that the 7 STM slots of the STM contain chunks of 2 pieces each, a total of 20 pieces is obtained for the 2 positions, which is in accordance with the results obtained in Frey and Adesman's experiment (their subjects replaced correctly about 10 pieces by position).

A logical extension of Frey and Adesman's (1976) study of memory for either of two positions is to ask subjects to reconstruct both positions. This procedure has been extended up to five positions by Gobet and Simon (1992, in press-b), where boards were presented in short sequence for 5 s each, and up to nine positions by Cooke et al. (1993), who used a presentation time of 8 seconds. Both teams found that, although there is a decrease in the percentage of pieces recalled correctly, the number of pieces recalled increased as a function of the number of boards presented. In general, the limit in the number of boards to be recalled with some level of accuracy (say 60%) seems to be around four or five. There are two exceptions: first, one subject in the Cooke et al. study (1993, p. 342) who (partially) recalled seven boards out of nine and who may have used a mnemonic technique based on associations with names of famous players to enhance his memory; and second, the subject trained by Gobet and Simon (in press-b) to apply a similar mnemonic technique.

At first blush, these results seem to squarely refute Chase and Simon's theory. However, a noticeable result of Gobet and Simon's (in press-b) study was that, when Chase and Simon's 2 s boundary technique is used to estimate chunk size, large chunks were found for masters (up to 15 pieces). This result contrasts with the relatively small chunks found in the original study (see Gobet & Simon, 1995b, for potential explanations of this difference). If chunk size is larger than what proposed by Chase and Simon, then their model can account for the interference and multiple board data, assuming that subjects use the strategy of keeping at least the largest chunk for each position in STM. Supposing that masters are able to recognize such large chunks would, however, seriously inflate the estimated number of chunks in LTM: since the likelihood of recognizing such a chunk is low, only a huge chunk database could account for these recognitions. An alternative theoretical line is taken by the template theory, which avoids this inflation in chunk number by assuming that information can be rapidly stored into template slots. The presence of templates explains why the multiple board task is tractable for masters, at least up to four or five boards: only one pointer needs to be placed into STM per position in order to remember the "spirit" of each position. Simulations of the CHREST implementation of the template theory show that this explanation fits the data well (Gobet et al., in preparation). The model relied on STM storage and, given that a chunk had been a sufficiently long time in STM, on LTM storage. However, the model does not implement (yet) the idea that templates, which are in fact an organized part of semantic LTM, probably receive some activation when they are accessed. This may explain that players, both in the multiple board experiment and in Charness's (1976) interference experiment, may still access information when it seems to have disappeared from STM.[7] The idea of LTM activation has been recently implemented in a EPAM-model of the memory of an expert mnemonist (Richman, Staszewski & Simon, 1995).

To account for the interference data, Charness (1976) proposed that traces are organized and undergo, during the first seconds of presentation, a deep treatment that protects them against retroactive interference. Chess experience determines the speed with which more elaborated codes are accessed. A similar idea was proposed by Frey and Adesman (1976) who concluded that Chase and Simon's model has to be given up in favor of a model stressing depth of processing. As no specific mechanisms were proposed, it is difficult to evaluate these proposals. Cooke et al. (1994) proposed that players encode one high-level description per position, allowing a efficient use of STM, though they did not rule out LTM storage. The details of such high-level descriptions were not specified, however. It seems that this explanation can be subsumed as a special case of the template theory, where templates provide players with verbal labels for characterizing positions. Note that Cooke et al. (1994) do not offer any alternative mechanism when no high-level description is available (De Groot & Gobet, in press, discuss in length the case of a subject recalling a position almost perfectly but clearly indicating in his verbal protocol that no high-level description was available).

The long-term working memory theory accounts for the interference and multiple board results by assuming that strong players encode each position rapidly into a retrieval structure. In addition, as indicated by Figure 4 of Ericsson and Kintsch (1995), the retrieval structure is connected to schemas in LTM, which insure redundancy in encoding and offer an explanation for the large chunks found by Gobet and Simon (in press-b), and for the high-level, prototypical position descriptions used by players. Several aspects of the theory are not worked out in sufficient detail, however: Is the same retrieval structure used to encode each position, or are copies of the retrieval structure used? In the first case, how are interferences between boards avoided? Why is there a limit at around 5 boards for most subjects? Why did the subject studied by Gobet and Simon (in press-b) reach a plateau at 8 boards?

4.2.2 Random Position[8]

One of the basic findings of De Groot (1946/1978) was that chess masters were able to recall almost perfectly a chess game position presented for a short amount of time, whereas less skilled players were only able to replace a few pieces. Although De Groot was careful to control for the general intellectual background of his subjects in order to avoid most of the potential confounding variables, it was not possible to rule out the possibility that his chess masters obtained better results because of better (visual) memory. A control task would be necessary, where chess masters would not show any superiority over other players.

4.2.2.1 Recall experiments.

Chase and Simon (1973a) provided such a control task by using chess positions in which the pieces were arranged randomly on the board.[9] With a presentation time of 5 s, they did not find any recall difference between their 3 subjects (a master, a class A player and a beginner) on this control task. This result had a dramatic impact in cognitive psychology and is a classic result found in most cognitive psychology textbooks. However, matters are more complicated. Gobet and Simon (in press-d), reviewing a dozen of experiments where random positions were used as control positions with a presentation time less or equal to 10 s, recently showed that there is a correlation between skill level and recall performance even with random positions, although it is rarely statistically significant. The lack of significance may be explained by the lack of power of most experiments reviewed: the sample size is small, as is the effect size (when confronted with random positions for 5 seconds, masters place an average of 5.5 pieces, while the weakest players—below class B—place an average of 2.6 pieces).

In a re-analysis of De Groot's (1946/1978) protocols, Reynolds (1982) found that weak players focus their attention upon piece locations, while strong players are more interested by the roles of important squares, usually squares in the center of the board. In order to test the generality of this behavior, Reynolds carried out an experiment in which he used "random" positions and varied the level of centralization of the pieces. Good players obtained better results if, and only if, stimulus positions contained a grouping directed toward the center. However, Reynolds's results are difficult to interpret, because, as is shown in Gobet (1993a), the positions he used are not completely random, as they do not respect the equiprobability for a white or black piece to be located in White's side (from the 1st to the 4th rank) or in Black's side (from the 5th to the 8th rank).

4.2.2.2 Recognition experiments.

There is no interaction between skill and degree of meaningfulness in the recognition task: strong players keep their superiority for recognizing random positions. In addition, the deficit in comparison with game position is weak, if at all present (10% in Saariluoma, 1984), Goldin (1979) even finding a 2% superiority in favor of random positions. Presentation duration (50 s per position in Goldin, 1979; 8 s in Saariluoma, 1984) does not influence this result. Goldin proposes that subjects' chess knowledge allows them to encode logical parts in random positions. Such a strategy is sufficient for recognition purposes, as a complete representation is not necessary. Lories (1984) explains the superiority of strong players with random positions by proposing that they profit from the relatively long presentation time and use a strategy better adapted to the demands of the situation. As the random character of the position makes it inappropriate to use semantically rich knowledge, Lories proposes that strong players chose to process these positions at a shallower level, for example the one proposed by MAPP. As for weaker players, they use a less efficacious strategy, consisting of encoding positions by noticing geometrical regularities.

4.2.2.3 Theoretical implications.

Theoretically, the most interesting result of this section is that strong players do maintain some superiority when recalling briefly presented random positions. As discussed by Gobet and Simon (in press-d), this is what is predicted both by the chunking and the template models: a large database of chunks is more likely to recognize adventitiously chunks in a random position than a small one. Simulations described in Gobet and Simon (in press-c) show that larger nets do indeed perform better at recalling random positions than smaller nets. It is unclear how high-level descriptions theories account for this result, because random positions, by construction, do not map to high-level descriptions. Nor is it clear how the level-of-processing approach explain this result, since subjects of various skill levels seem to pay attention to the same aspects of the position, as indicated by their verbal protocols (Gobet, 1993a). Finally, the long-term working memory theory, which suggests that each slot in the 64-square-isomorphic retrieval structure allows a rapid encoding into LTM, does indeed predict an effect of skill for random positions, but an effect that is much stronger than is found. As mentioned above, even masters recall only an average of 5.5 pieces. A possible amendment of the theory is to give more emphasis to elaboration encoding through LTM schemata, and less to the retrieval structure, which would account for the data on both game and random positions recall. However, it is doubtful that such an amendment would be in the spirit of the skilled memory theory, which precisely emphasizes the role of retrieval structures.

Of the four theories, the retrieval structure theory is the one telling us most about the recognition task. The retrieval structure theory accounts for these results mainly by the presence of knowledge-based associations, since reliance on the retrieval structure would result in considerable retroactive interference when many positions are presented. Although not explicitly mentioned by their authors, the chunking theory, the template theory, and the knowledge-based theories could use some similar time tagging or contextual cues encoding mechanisms, possibly mediated by subjects' strategies, as suggested by Lories (1984).

4.2.3 Number of Pieces

A standard result of learning psychology is that, for meaningless material, learning time per item increases with the quantity of material to learn (Thurstone, 1930). Chess research shows that this law does not apply for meaningful material. In their seminal study, Chase and Simon (1973a) found that, presentation time being equal, their subjects (with the exception of the beginner) retain more pieces in middle game positions (average number of pieces = 25) than in endgame positions, where few pieces are typically left (average number of pieces = 13). As their strongest subject, a master, recalled about 8 pieces in endgame positions, the hypothesis of a ceiling effect may be ruled out. Saariluoma (1984, exp. 3) replicated this result, presenting positions containing 5, 15, 20 and 25 pieces. He also found an interaction between skill level and number of pieces presented: while there is a positive correlation for masters between the number of pieces recalled and pieces presented, there is no correlation for beginners.

Using a chunking framework, Saariluoma (1984) proposed that strong players recognize various known constellations in positions containing numerous pieces (opening and middle game positions), but that the endgame positions are less predictable and, therefore, harder to code as chunks. A similar explanation may be given by the template theory and, to some extent, by the knowledge-based theories. For example, it can be pointed out that, since the chess game tree expands exponentially, endgame positions are less likely to belong to a known category (see De Groot and Gobet, in press, for an in-depth discussion of the properties of the chess game-tree). If this explanation is true, then <u>typical</u> endgame positions should be memorized in an almost perfect way. As far as I know, this has not been established experimentally.

That masters cannot recall all pieces of an endgame position seems rather damaging for the long-term working memory theory: few pieces need to be encoded, and these pieces in general share semantic relations, as they are taken from master games. It is unclear why the retrieval structure does not allow all pieces to be encoded.

4.2.4 Recall of Games

The recall task has also been applied to moves. After subjects have been given 30 seconds to familiarize themselves with a position, Chase and Simon (1973b) present a sequence of 20 half moves, with 5 s for each half move. A recall task follows immediately. These authors found that there exists a correlation between recall scores and skill, even for random moves sequences. Reaction times indicate that players are slower to reproduce random moves. Chase and Simon stress the parallelism between these results and those obtained with the recall of pieces, and note that the main difference (strong players maintain their superiority for random moves sequences) may be explained by the relatively long time of exposure (about 2 minutes in total). Such an interval may allow numerous reorganizations in the material and a permanent storage into LTM. The analysis of reproduction errors and pauses of their subjects suggests a hierarchical organization of moves, each episode being organized around a goal.

In an experiment using blindfold chess, Saariluoma (1991) dictated moves at a rapid pace (one piece moved every 2 s), from three types of games: one game actually played, one game where the moves were random but legal, and one game where the moves were random and possibly illegal. Results show that masters were able to indicate the piece locations almost perfectly after 15 moves for the actual game and legal random games, but that the recall of random illegal games was less than 20%, close to the performance of novices, who were outperformed in the two other conditions. For Saariluoma, these results support the chunking theory. Random legal games drift only slowly into positions where few chunks can be recognized, and, therefore, allow for a relatively good recall. The further away from the starting position, the harder recall should be, which is what is observed (the recall with legal random games drop to 60% after 25 moves, while the recall of actual games stays close to 90%). Random illegal games move more rapidly into chaotic positions, where few chunks may be recognized and recall is, therefore, low. In another experiment, Saariluoma (1991) verbally dictated 10 actual games simultaneously, by sequences of 5 to 10 moves, at a self-paced rate. He found that masters were able to remember correctly all games and to generate the positions after 15 and 25 moves with a 90% accuracy. These results, with material that vastly overloads working memory capacity, suggest that blindfold players have a rapid access to LTM.[10]

As mentioned by Chase and Simon (1973b), the rather long presentation time of these experiments allows subjects to access information in LTM; in particular, with actual games they may access chunks, templates, schemata or prototypes. The template theory proposes that moves and sequences of moves may be chunked, in the same way groups of pieces are chunked. Strong players, who have more chunks of pieces and of moves, are expected to perform better than weaker players in this task. The long-term working memory explanation is that the retrieval structure allows players to rapidly update information about the position and to create retrieval cues about each move.

It is more difficult for the knowledge-based theories to explain masters' superiority in recalling random legal moves, except by supposing that masters are "more familiar" with the chess material. The chunking theory explanation is that strong players, as they have more chunks with which they can associate information about moves (remember that the presentation time is long), are more likely to find such chunks even in random positions. The template theory uses the same reasoning, with the addition that strong players have chunks of moves as well. The long-term working memory explanation is the same as with actual games.

As for random illegal games, masters' poor results are what is predicted by the knowledge-based, chunking, and template theories (see above Saariluoma's explanations). With respect to the retrieval structure explanation, these results suggest, however, that integration with schemas in LTM is necessary for securing memory traces, which does not happen with this type of material. Shifting the emphasis to LTM schemas would, however, decrease the explanatory power of the retrieval structure, which is central in the Ericsson and Kintsch (1995) account.

4.3 Modality of Representation

The chunking theory and the template theory propose that the main access to chess chunks is visual (though other routes, such as verbal descriptions, are present as well), and that the mind's eye, or the internal representation, uses a visuo-spatial mode of representation. High-level knowledge theories give more importance to abstract types of representation, while the level-of-processing approach indicates that stronger players use less visual and more abstract modes of representation than weaker players. Finally, the retrieval structure theory is neutral as far as the mode of representation is concerned.

Chase and Simon (1973b) examined the role played by the type of presentation of the stimulus. Their goal was to eliminate the theoretical explanation that the chunk structures they had isolated were due to a reorganization during the output rather than to perceptual processes during encoding. They presented half of the positions with standard board and pieces, and the other half with grids containing letters. During recall, the same dichotomy was used. Response modality did not influence the percentage of correct answers, but a large difference was observed with the stimulus modality, their class A player obtaining about twice as many correct pieces with board presentation than with letter diagrams. Interestingly, this difference disappeared rapidly with practice: after about one hour of practice, their subject did not show differential results between boards and letter diagrams. Chase and Simon interpreted these results as a confirmation of the perceptual character of chunks but did not offer any detailed explanation of the learning mechanism that allows the rapid transfer to the letter diagrams. In another experiment, class A players did not exhibit any difference in the recall of positions shown with diagrams (such as the ones found in chess journals or books) and positions with standard pieces and board. The beginner was very sensitive to these modality differences.

Brooks (1967) found that, when sentences are referring to spatial representation, it is better to listen to them than to read them. Using this background, Charness (1974, study no 5) tested the hypothesis that statements describing a chess position are represented with a spatial structure. His results indicated that chess players obtain a better retention level when they listen to the description of a position[11] than when they read it, whereas no difference was to be found with non-players. Moreover, an imagery scale showed a clear visualization decrease in the reading condition. Charness concluded that chess players possess a specialized (spatial) representation, which they can access even when information is presented in a non-spatial code.

In another experiment, Charness (1974, study no 6) was interested in the way scanning order of a position affects chunking of pieces. Pieces were presented verbally, with 2.3 s per piece, following three conditions: (a) grouping according to the relations proposed by Chase and Simon (1973a); (b) presentation by columns; and (c) random order. Charness found that the type of presentation strongly influences recall performance, with decrease from the chunking to the random presentations. He showed also that players restructure piece groupings, mainly when the grouping used in the presentation does not offer much chess meaning (scanning by column and random scanning). Finally, Charness proposed that differences in scanning strategies could account for part of the differences found in the memory task.

One could object that this last experiment did not teach us very much about chess players' mechanisms for memory and perception, as it is not very common for a player to memorize a dictated position. In the last experiment of his Ph.D. thesis, Charness (1974, study no 7) countered this criticism. He used the same technique as in the experiment just described, with the difference that the presentation was done visually, a movie exposing each piece for 2.3 s. As with auditory presentation, the type of board scanning affected recall, chunk and column presentations allowing better scores than random presentation. In addition, chunk structure was best recalled in the chunk condition. The most striking result, however, was that there was a global performance gain (18%) for the visual modality against the auditory modality. Although Charness stressed the difficulty involved in unraveling the exact processes that underlie this difference, he suggested several hypotheses: visual presentation decreases the likelihood of translation errors, the duration of visual code is longer, and the presence of a chess board makes it easier to generate relational structures between pieces.

Motivated by Baddeley's (1986) theory of <u>working memory</u>, Bradley, Hudson, Robbins and Baddeley (1987) studied the effect of interfering conditions during the presentation of chess positions. They found that a verbal task (repeat "the" every second) had only a minimal effect on performance, while a task aimed at suppressing the visuo-spatial system (to type a predefined series of keys on a calculator with the index of the non-preferred hand) and the central executive (to randomly generate letters) caused a significant loss of performance (more than 2/3 in comparison with the control group). Interestingly, these authors observed a similar pattern of results with chess problem solving used as interference task, with the qualification that performance does not decrease as drastically (only 1/3). Some of these results—effect of visuo-spatial interference and absence of effect of articulatory interference—have been replicated by Saariluoma (1992), whose subjects had to count the number of minor pieces (Bishops and Knights) or solve chess quizzes.

Blindfold chess has shed interesting light about the type of representation players used. When presenting Binet's (1894) contribution, I mentioned the role played by knowledge (erudition, in Binet's parlance) in blindfold chess. Subsequent research has confirmed that role. In his description of (simultaneous) blindfold chess, world champion Alekhine acknowledges that the quality of blindfold games is inferior to games played in normal conditions, and stresses the importance of logical rather than visual memory (Bushke, 1971). Fine (1965), who was a world class player before becoming a practicing psychoanalyst, has carried out an introspective study on his own playing of blindfold chess. He emphasized the importance of chess knowledge, which allows the expert player to grasp the position as an organized whole, and the capacity to visualize the board clearly. In an extensive review of the literature on blindfold chess, Dextreit and Engel (1981) note that positions are encoded as key-sentences (e.g., "Panov attack; White builds up an attack on the King's side, Black tries to counter-attack on the center."), corresponding to the critical moments of the game.

Saariluoma (1991) studied experimentally various aspects of blindfold chessplaying. His approach was to dictate sequences of moves from games at a rate of 2 seconds per piece moved and to probe the recall of the positions after 15 and 25 moves. Using Baddeley's (1986) framework, he showed that concurrent[12] interfering tasks had a deleterious effect when they were visual or related to the central executive, but not when they were simply articulatory. These three tasks had no effect when given as posterior interference tasks. Saariluoma also showed that, while masters were almost perfect in recalling positions from master games, they showed a sharp decrease with random games made of legal moves (only 60% correct after 25 moves) and an even sharper decrease with random games made of illegal moves (almost zero percent correct after 25 moves).

In conclusion, there is very strong evidence that chessplayers use a visuo-spatial mode of representation, which is captured by both the chunking and the template theories. This visuo-spatial mode does not imply, as was incorrectly implied by Ericsson and Kintsch (1995, p. 237), that the chunking theory predicts difficulties in encoding the type of verbal, serial inputs used by Saariluoma. Information on the location of single pieces may be stored in the mind's eye, and chunks recognized by scanning part of it. In addition, the relatively long time used for dictating pieces may be used to create a few new chunks. Ericsson and Kintsch also point out that the presence of effect with concurrent interference, but the lack of effect with posterior interference (Saariluoma, 1991), offers strong evidence for LTM encoding. Given the rather long presentation time (at least 60 s = 2 s times 15 pairs of white and black moves), this could be accounted for by traditionnal LTM encoding, without using the concept of long-term working memory. With this explanation, visuo-spatial or central executive concurrent interference would hinder LTM encoding processes.

Frequent mentions of high-level representations by masters offer support for the high-level and depth-of-processing theories but are not incompatible with the template approach, which proposes that several routes (visual, verbal, or conceptual) may lead to the same LTM node, which may in turn yield the same visuo-spatial representation in the mind's eye. As mentioned in the introduction of this section, the long-term working memory approach does not specify in detail the mode of representation used by chessplayers.

4.4 LTM Organization

Holding (1985) notes that, in contrast to the breadth of STM research, LTM research has been quite modest. To be precise, and using a dichotomy proposed by Simon (1976), semantic LTM has received little attention, while recognition LTM memory, which constitutes an essential component of the chunking theory, has been studied in some depth. This section first discusses empirical evidence on chunks. Then, it presents data on hierarchical organization and conceptual organization. Finally, it discusses data directly related to the presence of a retrieval structure.

4.4.1 Evidence for Chunks

The basic analyses leading to chunk identification by Chase and Simon (1973a) have been recently replicated by Gobet and Simon (1995b). This section presents additional converging evidence that supports the psychological reality of chunks as defined either by numbers of chess relations or latency in placement.

It has been shown that pieces presented at a rapid rate (about 2 s per piece) are better retained when they are presented according to the chunk relations proposed by Chase and Simon (1973a) than when they are presented by columns or randomly; this result holds for both verbal and visual presentation (Charness, 1974; Frey and Adesman 1976). Interestingly, chunk presentation yielded better recall than presentation of the entire position for the same total time (Frey and Adesman 1976).

The partitioning technique devised by Reitman (1976) for studying GO players' memory has offered supporting evidence for a LTM organization based on chunks. Chi (1978) showed that chunks were sometimes overlapping, which was also found in computer simulations using the chunking approach (De Groot & Gobet, in press). Second, she found that the amount of time taken to place pieces crossing a chunk boundary (as defined by the way subjects partitioned the board after recall) was on average longer (about 3 s) than the amount of time taken to place pieces within a chunk (around 1.5 s). Chi notes that this result supports Chase and Simon's (1973a) estimate that it takes at least two seconds to access a new chunk and less than two seconds for retrieval within a chunk. Freyhoff, Gruber and Ziegler (1992) also used a partitioning procedure, with the addition that subjects had both to divide the groups obtained in a first partition into subgroups and to combine the original groups into supergroups. At all levels of partitioning, masters selected larger clusters of pieces than class B players did. In addition, the chunks they detected at the basic level corresponded to the chunks identified by Chase and Simon (1973a), both with respect to size and with respect to the pattern of relations between pieces.

Gold and Opwis (1992) used hierarchical cluster analysis to analyze chess players' chunk structures. The clusters they identified with this technique were similar to those identified by latencies (e.g., castle positions, chain of pawns, common back-rank piece positions). Using a sorting task, Gruber and Ziegler (1990) found that chess players used sorting units similar to the chunks identified by Chase and Simon (1973a, 1973b). However, the frequency of such chunks was less frequent with stronger players, who tended to use overlapping sorting criteria that grouped chunks together. Consistent evidence was found by Gruber (1991), who showed that, in a task consisting of guessing a position (see also Jongman, 1968; De Groot & Gobet, in press), weak players asked questions about the location of single pieces, while experts asked questions about the past and future proceeding of the game, about plans and evaluations, etc...

These result support the concept of chunks but also indicate that strong players use higher types of description, as proposed by the knowledge-based theories.

4.4.2 Number of Chunks in LTM

Obviously, the question of the number of chunks in LTM is of importance only for the chunking and template theories, among the four theories being compared in this paper. Simon and Gilmartin's estimate of the number of chunks necessary to reach expertise (about 50,000) was challenged by Holding (1985, 1992). Holding proposed that this number could be decreased to about 2,500 if one is willing to assume that patterns are encoded independently of color and of location.[13] A pattern shifted horizontally and/or vertically by several squares would thus be encoded by the same chunk in LTM because the functional relations among the pieces are maintained.

Gobet and Simon (in press-c) tested Holding's claim by using positions that had been modified according to various mirror-image reflections (for example, White and Black, or left and right are swapped). Their hypothesis was that recall of non-modified positions should be better than recall of modified positions, as the former should elicit the recognition of more chunks than the latter. They found that recall was slightly, but statistically significantly, impaired by such distortions. The effect was particularly clear when positions were pooled conditionally to the presence of reflection about the vertical axis (swapping of the left and right sides). Converging evidence on the importance of location in encoding chess knowledge is provided by Saariluoma (1994), who distorted positions by swapping two of their quadrants (note that Saariluoma used modification by translation, while Gobet and Simon used modification by reflection). He found that the recall of the translated pieces was dramatically reduced in comparison with that of unmoved pieces.

Taken together, these results suggest that spatial location is encoded in chunks and add plausibility to Simon and Gilmartin's estimate of the number of chunks necessary for expertise. Gobet and Simon (in press-c) report a simplified chunking model that was able to show the same effects as human subjects in the mirror-image modification experiments. Knowledge-based theories could account for these results by pointing out that LTM schemas or prototypes are harder to access with the modified positions. (However, knowledge-based theories would have a harder time with another experiment reported by Saariluoma, 1994, who constructed positions by taking quadrants from four different positions; players had a recall performance close to game positions, although construction of the positions made access to LTM schemas difficult.) Finally, it is unclear how the long-term working memory accounts for the results reported in this section. Every "square" in the retrieval structure has the same encoding power, hence it is unclear why modified positions should be recalled less than unmodified positions. A possible explanation, based on the assumption that the retrieval structure encodes relations between pieces as well as their location, does not help: the mirror-image positions contain the same set of relations between the pieces as the original game positions, with the qualification that the direction of relations is modified.

4.4.3 Hierarchical Organization

That expert memory uses hierarchical structures has been a recurrent theme in psychology (Cleveland, 1907; De Groot, 1946/1978; Chase & Simon, 1973b; Chase and Ericsson, 1982). This hypothesis has been tested by Freyhoff et al. (1992) with chess. In one of their experiments, these authors have used the partitioning technique applied by Reitman (1976) in her study of GO players. In this technique, subjects are asked to divide a position into meaningful units, which constitute, according to Freyhoff and his colleagues, the basic level (cf. Rosch, 1973). In addition, Freyhoff et al. asked their subjects both to decompose and to group these units. It was found that, for the three levels of partitioning, masters have delimited larger constellations than class B players. Results also indicate that base level constellations are similar to the chunks as defined by Chase and Simon (1973a). In another experiment, Freyhoff et al. found that, in an evaluation task after a brief presentation (5 s), masters were able to give judgments on the entire position, while amateurs' remarks were limited to isolated pieces and to superficial features. (For a similar conclusions and examples of protocols, see De Groot, 1946/1978, Gobet, 1993a.) Freyhoff et al. note that, almost without exception, masters make their evaluations at the superordinate level (Rosch, 1973) and that these evaluations were combined with dynamic reflections on the past or future course of the game.

Although these results seem to support the hypothesis of a hierarchical encoding in LTM, caution is required about their theoretical implications. First, it could be the case that this hierarchic character is only an artifact of the experimental method, which required precisely three levels of partitioning. Second, as is pointed out by Freyhoff and his colleagues, such a decomposition of the position into meaningful units not only is based on activation of preexisting knowledge but also requires a creative act. Finally, instructions used by these authors explicitly invited the subjects to partition the board without intersection. Reitman (1976) with GO and Chi (1978) with chess have shown, however, that a stone or a piece could belong to several chunks. Redundancy in encoding, if it does not exclude the possibility of a hierarchic representation, excludes, however, such ideal tree structures as the ones given to us by zoological taxonomies.

Retrospective protocol analysis after the reconstruction of a position offers some evidence for a hierarchical representation of chess positions in memory (De Groot & Gobet, in press; Jongman, 1968; Freyhoff, Gruber and Ziegler, 1992). Typically, masters do not refer very often to isolated chunks (in the sense of Chase and Simon, 1973a, 1973b), but try to actively reconstruct the position, referring to prototypical positions. Weaker players (perhaps below class A) behave more according to the Chase and Simon model and reconstruct the position by means of isolated chunks.

Hierarchical organization is captured by the four theories discussed in this paper. It is most apparent in the template theory, whose computer implementation is based on a recursive chunking mechanism (Gobet, 1993a, 1993b; Gobet et al., in preparation).

4.4.4 Conceptual Representation

High-level representation and depth-of-processing theories clearly emphasize the role of conceptual representation. The long-term working memory theory suggests ways in which connections may occur between the retrieval structure and the conceptual information held in LTM, although these suggestions are not worked out at a detailed level. The chunking theory emphasizes the role of perceptual aspects of chess memory, which does not mean, however, that it denies the importance of conceptual knowledge (cf. Chase & Simon, 1973b, p. 260). Finally, the template theory specifies conceptual knowledge in some detail, with templates acting as conceptual prototypes.

All four theories, therefore, agree about the role of conceptual knowledge, so the data presented in this section should not be expected to discriminate strongly between them. More interesting, for this purpose, are the empirical results about what happens when it is not possible to use conceptual knowledge (see above the section about random positions). Evidence about typicality will discussed first, followed by evidence about the effect of semantic orientation. A theoretical discussion ends this section.

4.4.4.1 Typicality.

While it is unclear what typicality really is in chess, it is possible to state what typicality is not. Guessing experiments as well as information theory analyses clearly show that typicality is not knowledge of first-order location probabilities of the pieces on the chess board (De Groot, 1966; De Groot & Gobet, in press; Jongman, 1968). Rather, typicality relates to highly specific (higher-order) kinds of knowledge.

Little experimental work has been done on the notion of typicality.

Strong players obtain better scores both in recognizing and in recalling game positions, with short as well as with long presentation time (Goldin, 1978a, 1978b, 1979; Saariluoma, 1984). This effect of typicality is somewhat surprising, as it does not correspond to results obtained with verbal material, where it has been shown that frequently used words are better recalled that rare words, but that the inverse relation applies for recognition tests (Kintsch, 1970). One difficulty with research on typicality relates to how to define this concept operationally. Goldin asked a master to assess the typicality of the positions and used only the most typical and the most atypical positions. However, the vagaries of this type of operationalization have been commented on by Gobet (1993a), who found only very weak correlations between 5 players (two grandmasters, one international master and two experts) asked to scale a set of positions according to their typicality.[14]

Several theoretical propositions have been done about typicality in chess. Goldin's (1978a) has suggested that typical positions may constitute prototypes, and the deviations from the default values may be noticed. Selz's (1922) concept of "knowledge complex," championed by Jongman (1968), is in the same spirit. The long-term working memory seems to de-emphasize the role of typicality, as the same structure allows encoding any type of position, although, as mentioned by Ericsson and Kintsch (1995), the presence of LTM schemas may make some positions easier to encode. This aspect of their theory is left largely undeveloped, however, in the case of chess expertise. Finally, templates may be seen as implementing the prototypes proposed by knowledge-based theories.

4.4.4.2 Effect of semantic orientation.

The level-of-processing approach (Craik & Lockhart, 1972) has spawned some interesting work in chess research. Several authors have shown that the presence of supplementary information on the position, even of an abstract kind, enhanced subjects' performance. Goldin (1978b) obtained such results by having her subjects study the previous moves of the game. She found, on the one hand, that stereotyped, highly typical positions were better recalled by all subjects and on the other hand, that previous study of the game significantly increased the correctness of the responses as well as the confidence that subjects placed in them. Frey and Adesman (1976, exp. 1) observed similar results when presenting the moves leading to the position to be remembered. It should, however, be noticed that in both Goldin's and Frey and Adesman's experiments, the level-of-processing variable is confounded with the presentation-time variable. In another experiment by Frey and Adesman (Exp. 2), six slides of 2 s each cumulatively presented the pieces of one position.[15] The critical variable was the semantic meaningfulness of the sequences (chunks according to the definition of Chase & Simon, 1973a) or the lack of it (pieces are displayed by columns). Frey and Adesman showed that meaningful groupings allowed for better recall of the position.

The preceding results suggest a possible interaction between the contextual information given during the presentation and the skill of the players. Lories (1984) proposes that this type of information may be integrated by players having a rating as low as 1400. Horgan and Morgan (1990) have studied the question with children, whose strength spanned from 1100 to 2100 ELO. They found that the performance in the normal recall task is significantly correlated with ELO rating and with age, but that the strength of these correlations diminishes and even becomes statistically non-significant when contextual information (such as: "It is White to play. White is ready for attack.") is given during the presentation of the position. Cooke et al. (1993) showed that players took better advantage of a high-level description of a position when the description is given before rather than after the presentation of the position itself. Finally, giving some partial cues on the position to reconstruct, such as the location of some pieces, has no effect on recall, with tournament players as well as with casual players (Watkins, Schwartz & Lane, 1984).

Varying the instructions given to their subjects, Lane and Robertson (1979) observed that recall performance varied as a function of the level of semantic significance with which subjects could examine the position. Players who had only a structural task to perform (to count the number of pieces located on white and black squares) obtained worse results than the ones asked to judge the position and try to find the best move. This difference disappeared, however, when subjects were notified in advance that they would have to reconstruct the position. This relation between retention and experimental instructions is found with novices as well as with good amateurs. On the other hand, no interaction was found between skill level and experimental instructions. Lane and Robertson (1979) bring these observations together with the results obtained with random positions and suggest that they fit Craik and Lockhart's (1972) model better than Chase and Simon's (1973b). Encoding is, according to them, a function of the level of processing.

The same types of effect are found with recognition tasks. Deep semantic treatment of the material, such as choosing the best move or evaluating the position, makes recognition easier in comparison with a superficial treatment, such as counting the number of pieces on black squares or copying the position (Goldin, 1978b). Note, however, that recognition percentage is high even with superficial tasks (more than 70% for class A players). According to Goldin, these results support Chase and Simon's (1973, b) conclusion about the importance of perceptual processes in chess players and suggest that pattern recognition mechanisms are rapid, automatic, and hard to inhibit.

4.4.4.3 Theoretical implications.

As mentioned earlier, all four theories predict that supplementary information will improve the performance in recall. Clearly, the experiments related to level of processing (Goldin, 1978b; Lane and Robertson, 1979) support the high-level description and level-of-processing accounts of chess memory. These experiments have also often been cited as negative evidence against the chunking theory, though it is not clear it is so. According to the chunking theory, instructing subjects to pay attention to different aspects of the stimuli will determine what kind of chunks will be placed in STM. While it is true that MAPP (Simon & Gilmartin, 1973) simulated only perceptual intake of chess positions, there is nothing in the theory that precludes other access to chunks. The template theory makes this point explicit by emphasizing that several discrimination routes may lead to the same chunk. The theory also predicts that giving a high-level description before the presentation of a position enhances recall more than when it is given after (cf. Cooke et al., 1993): in the former case, but not in the latter, subjects rapidly access a template—it is strongly suggested by the experimenter!—and have then time either to store smaller chunks or individual pieces into STM or to use the template to correct its default values or fill in slots without default value. Finally, the retrieval structure theory specifies that conceptual information should enhance recall but does not give any details on the mechanisms involved.

4.4.5 Direct Evidence for Retrieval structures

Ericsson and Oliver (1984), cited by Ericsson and Staszewski (1989), developed a series of experiments using blindfold chess to test the plausibility of retrieval structure with chess players. In one experiment, their subject (rated just below master level) had to memorize a 40-move game, whose moves were individually presented on a computer screen,[16] using algebraic notation. During the test phase, he was presented with the notation of a square, say "d4," and was asked to name the piece located on this square, if any, as fast as possible. The entire board was probed in a random way.

The first important result is that their subject took only two seconds to make a move in the blindfold condition.[17] Ericsson and Staszewski report that this time was faster than the corresponding latency in the perceptual condition, where the subject was normally playing the moves on the chess board. Such a speed of encoding did not spoil his accuracy in answering the probes (over 95% correct). The average latency to answer the probe was around 2 s in the blindfold position and around 1 s when he could see the board.

In another experiment, their subject had to memorize two positions, presented visually on diagrams. He was then probed following one of three presentation orders: (a) in the sequential condition, all squares of one position were probed, and then the squares of the other position; (b) in the alternating condition, each position was alternatively probed; (c) in the last condition, squares were randomly selected from either position. For each position selected, squares were probed randomly.

After a few trials where results among the three conditions were indistinguishable, a clear pattern emerged: the random and alternate conditions remained close (2.4 s and 1.9 s per probe, on average), while the sequential condition's probe became almost as twice as fast (about 1.0 s). The random condition showed no reliable speed-up with practice, the alternate a slight one, and the sequential an important one. In the sequential condition a peak appears when the first square of the second board is probed (about 1.4 seconds), after that the pace was as fast as in the first position. Finally, the random condition showed a speed up when the probes stayed in the same position.

Ericsson and Staszewski proposed that this subject used a common retrieval structure for the two positions, because he could access only one position at a time (cf. the increase of time when switching positions and the speed up when the position stayed the same). These results may, however, be as well accounted for by other explanations, among them: two retrieval structures (the increased latency would be caused by the switch of the 2 structures), hierarchical organization of chunks (the increased latency would be caused by accessing another supergroup of chunks), or two templates. Possibly, chunks and templates could be "unpacked" in a rapidly decaying internal representation, allowing a fast access to them. Unfortunately, Ericsson and Oliver's subject was not tested with random positions, which would have enable one to rule out some of these alternative hypotheses.

While undoubtedly interesting, this piece of research needs replication, because the only subject studied may not be representative of most chess players of his strength (Ericsson and Staszewski note that the difference between his play in normal and blindfold conditions was small, whereas most players' strength shows a more important discrepancy in these two variants of chess).[18]

4.5 Learning

What do our four candidate theories have to say about learning? For the empirical data on chess memory, three different cases may be considered: short-range learning (in the order of one minute), medium-range learning (in the order of weeks), and long-range learning (in the order of years). The chunking and the template theories use the same parameters as the EPAM theory (Feigenbaum & Simon, 1984), hence it is easy for these theories to make quantitative predictions. The key parameter here is that it take about 8 s to learn a chunk (Simon, 1976). The high-level and depth-of-processing approaches propose that learning consists of creating deeper levels of processing for the stimuli but do not offer either precise mechanisms or quantitative predictions. Finally, the retrieval-structure approach implies that learning consists of creating the retrieval structure, of speeding up the encoding and retrieval mechanisms, and of augmenting the schematic LTM. No time parameters are offered by the theory, hence it is not possible to make quantitative predictions.

4.5.1 Short-Range Learning

An approach that has produced interesting data has been to study the role of presentation time on the recall of positions. According to Chase and Simon (1973b), patterns stored in LTM are not equally familiar. This observation led them to propose that a dual mechanism operates during the perception of a position: at the beginning, familiar chunks are perceived; then, attention is focused on less familiar chunks or even on isolated pieces, which may be learnt. A consequence of this dual encoding and of the fact that the same pieces may belong to several chunks is that the probability of encoding a chunk is high at the early stage of perception and the probability of encoding isolated pieces (or of encoding chunks overapping with others) is high in the later stages. Thus, the quantity of information intake diminishes as the presentation time increases. The data of Charness (1981b), whose first interest was the role of age on recall, provides results compatible with this hypothesis for presentation times ranging from 1 to 4 s. Saariluoma (1984, exp. 5) has investigated this question with presentation times ranging from 1 s to 12 s and found that recall is a negatively accelerating curvilinear function of presentation time. The most complete set of data is provided by Gobet and Simon (1995a), using players ranging from weak amateurs to professional grandmasters. They systematically varied the presentation time from 1 second to 60 seconds and found that an exponential growth function[19] fits the data well ($r^2 > .90$ when fit is computed over skill level means). Both parameters of this function (B and c) vary as a function of skill: compared to weaker players, stronger players memorize more with a presentation time of one second and take better advantage of longer presentation times to improve their score. Using Chase and Simon's theoretical framework, it is unclear whether this second advantage is due to the fact that strong players learn new chunks faster or whether it is due to the fact that they recognize more chunks with additional time. As shown next, this relation between skill level and the parameters B and c remains when random positions are used.

The first results on the effect of presentation time on random positions were difficult to interpret. Djakow et al. (1927) found a superiority for the masters with a presentation of one minute. Only one position (one chess problem) was used, however, and the control group consisted of non-chessplayers, a situation that brings about the problem of less familiarity with the material. Lories (1987) examines the question in more detail and found a superiority of strong players in the recall of normal <u>and</u> random positions, again with a presentation of one minute. Unfortunately, this author used the positions constructed by Holding and Reynolds (1982), whose lack of randomness has been pointed out before. On the other hand, Chase and Simon's (1973a) master did not show superior progress over a class A player and a beginner in the learning of random positions (after an unsuccessful trial, the position was shown for 5 additional seconds).

Gobet and Simon (1995a) offer more systematic data, varying the presentation from 1 to 60 seconds with game as well as random positions. As with game positions, an exponential growth function provides an excellent fit to the data. The surprising result is that the data with random positions show the same pattern as those with game positions, with the qualification that the percentage of recall is lower with the former positions: players of different skills vary both in the amount of information they are able to memorize after an exposure of one second and in the rate with which they use additional presentation time, the stronger players showing a slight superiority in both cases. As with game positions, it is unclear whether this difference in the use of additional time is due to recognizing more chunks or to learning new chunks. Note that the task is far from trivial even for masters: on average, with an one-minute exposure, they are able to replace correctly only about 17 out of 26 pieces (68%).

Saariluoma (1989) provides some interesting results in connection both with the influence of meaningfulness on recall and with the role of presentation time. His methodology is similar to that used in the study of extraordinary memory (Chase & Ericsson, 1982, and Ericsson and Staszewski, 1989 for digit memory; Ericsson & Polson, 1988, for memory of restaurant menus). In his study, the positions are presented auditorily, one piece every 2 or 4 s (respectively 50 and 100 s for the entire position). An empty board is placed in front of the subjects. In concordance with Gobet and Simon's (1995a) data on the role of presentation time, results indicate that strong players are better in the recall of game as well as random positions, and that performance increases, for all players and types of positions, with the increase of latency between two successive pieces. Results also show that recall superiority for strong players remains when subjects have to memorize 4 game positions, but that players of all categories perform weakly with 4 random positions. Saariluoma concludes that chunking mechanisms do not consist only of activation of familiar patterns in LTM (how then can the effect of the duration of piece presentation and the effect of supplementary load of memory with additional positions be explained?), but that it is necessary to propose information processing mechanisms more complex to understand expert memory.

As mentioned earlier, the depth-of-level and high-level description theories do not have much to say about the results on short-term learning. Both the chunking theory, given a discrimination net sufficiently big to contain large chunks, and the template theory account for these results well (for game and random positions), with the assumption, already incorporated in the EPAM theory, that it takes about 8 seconds to create a chunk in LTM (see computer simulations reported in Gobet & Simon, 1995a). Given that no time parameters are indicated, it is difficult to judge the fit of the long-term working memory theory on the data with game position. The results with random positions and long presentation times seem, however, to be negative evidence against the latter theory: even masters recall little in one minute. Pointing out that no LTM schema can be used to supply additional integration is not of much help for this theory, because the long presentation time should allow the retrieval structure itself to encode a sufficient number of retrieval cues to allow an almost perfect recall.

4.5.2 Medium-Range Learning

Only few data are available on this topic. Ericsson and Harris (1990) examined the Chase and Ericsson (1982) model in its extreme consequences. They show that, after a training of about 50 hours in the recall of chess positions, a beginner obtains recall scores similar to that of an expert. No performance increase is to be found for random positions, and the performance is not decreased by the presence of interfering material. Contrary to what was found with chess players ranking from class A to master level (Gobet, 1993a), a global recall test done at the end of a session shows weak results. Behavior analysis of Ericsson and Harris's subject shows that she scans the 4 corners of the board in order to find familiar patters, that she identifies these patterns with mnemonic names (for example, the black configuration pawns f7, g6, h7, and Bishop g7 is dubbed "chandelier") and that, contrary to chess masters, she neglects the pieces located in the center of the board.

Gobet and Simon (in press-b) studied the creation by a master of a retrieval structure that allowed him to recall, with higher than 70% average accuracy, up to 9 positions presented for 8 s each, replacing as many as 160 pieces correctly. S's strategy was to associate each position with the corresponding element in a pre-learned list, which served as a retrieval structure. During recall, each element of the list serves as a cue to the retrieval of the corresponding position. S chose as elements of his cue list the names of chess world champions, in the order of their reigns, which allowed him to easily create meaningful associations with the positions.

Clearly, Ericsson and Harris's (1990) results do not fit the four theories in review, because their subject used a strategy that is <u>not</u> used by chess players. Gobet and Simon's results (in press-b) seem to indicate that masters can use a retrieval structure (not in the sense of the 64-square structure proposed by Ericsson & Kintsch, 1995, but more in the sense of the method of loci) to increase their capability of remembering several boards. This mnemonic technique seems compatible with the four theories reviewed here.

4.5.3 Long-Range Learning

As far as I know, there is only one longitudinal study about chess expertise. Charness (1989) has re-tested, with the same material, one subject, DH, who had participated nine years earlier in several chess experiments (Charness 1981a, 1981b). During this period, DH improved his level from about 1,600 ELO to a little more than 2,400, that is by four standard deviations. With respect to problem solving, it took less time for DH to choose a move, and he was exploring less different base moves (i.e., he was more selective) when tested nine years later. He was also faster to evaluate endgame positions and slightly more accurate. The size of his tree search did not vary much, nor his maximum depth of search. In the recall task, DH was close to perfect in the first testing session, and perfect nine years later. Chunks were larger and less numerous, and the between-chunks latencies were smaller in the second testing session. Charness suggests that this reduction in latency may be an indication that DH accessed chunks organized as a hierarchy.

Although generalization is risky with single-subject experiments, these results seem in harmony with the predictions of the chunking and template theories: increase in skill occurs mainly through differences in chunking (increase in the size of chunks, speed in accessing chunks) and not through an increase in search mechanisms. Note that the chunk size (on average 2.7 pieces) was smaller than what is predicted by the template theory, but this may be due to the recording technique used, similar to that used by Chase and Simon (1973a), which may break chunks down (Gobet & Simon, 1995b). The smaller inter-chunk latencies could speak in favor of this hypothesis. Alternatively, the reduction in inter-chunk latencies could support the hypothesis of a retrieval structure.

4.6 Problem Solving

This section reviews some empirical data on problem solving with direct implications for the study of memory.

When looking for a move in a position, players of all levels visit the same branch of the search tree several times, a phenomenon that De Groot (1946/1978) dubbed “progressive deepening.” It is interesting that, almost always, players do not directly access the position in the search tree they are interested in, but that they access it by generating moves in the mind’s eye from the stimulus position, which is normally in plain view. Within the framework of the retrieval structure theory, it is unclear why chess players should use progressive deepening, if encoding of a position (problem state) were fast and accurate. It would be easier for them to directly access the problem state they are interested in, without going through all the intermediary states from the stimulus position to the critical problem state. This difficulty does not plague the knowledge-based or the template theories: even masters are likely to use the same prototype or template in several states of their search. Because these theories state that it is not possible to make copies of prototypes or templates rapidly, their slots will be written over several times, with the consequence that interference between the various states will occur. Then, masters prefer to go over all the states of a sequence of moves rather than incur the risk of locating a piece erroneously—a consequence of this interference.

As stated above, Chase and Simon (1973b) proposed that skill in chess is mainly based on the presence in LTM of a great number of chunks encoding piece configurations, which trigger moves upon recognition. In order to test this hypothesis, Holding and Reynolds (1982) carried out an experiment in which they first asked subjects to recall a “random” position, and then asked them to find the best move in the position. No difference was found for the recall task, but good players were superior to weak players in the choice of move task. According to Holding and Reynolds, their results hit a harsh blow against Chase and Simon’s hypothesis: skill differences were found in a problem-solving task, but not in a memory task, which can be seen as a measure of pattern-recognition abilities. Holding and Reynolds proposed an alternative explanation of chess skill in which the role of memory is crucial during the evaluation phase of a position, but not during the perception phase.

It seems to me that Holding and Reynolds’s (1982) criticism is flawed, for three reasons. First, it is plausible to argue that, among the 50,000 patterns proposed by Simon and Gilmartin (1973), some of them are present even in random positions, but that their access takes longer, due to the lack of redundancy of their encoding in LTM. These chunks would then be useless in a recall task with short exposure, but useful in a problem-solving task where there is enough time for them to be accessed. Note that this explanation is consistent with masters’ clear superiority in the recall of random positions when the presentation time is long. Second, Chase and Simon (1973b) clearly stated that recognition mechanisms are not limited to the real position on the external board and occur during the anticipation of positions in the mind’s eye as well. It is plausible that chessplayers, asked to find a good move in a (for them) meaningless position, execute mentally a move according to simple heuristics, probably common to all players (control of the center, attack of opponent’s King, and so on), and that recognition mechanisms apply again to the position as it was updated in their mind's eye. The probability of discovering a known pattern at different levels of search would be higher for strong players, whose pattern database is richer. This interpretation would explain that strong players chose better moves, even in meaningless positions, without having to postulate a difference in the number of nodes searched.

Third, the random character of the positions used by Holding and Reynolds (1982) is disputable, since the hypothesis of a random distribution of White and Black pieces on each half on the board is not respected (Gobet, 1993a). As a matter of fact, Holding and Reynolds imposed three constraints to their positions (1. no King is in check; 2. no pawn is located on the 1st or 8th rank; 3. no piece is attacked by a pawn or is attacked without being defended) that restrain, to say the least, their random character. In these conditions, the greatest care is required for the interpretation of the experiments using these positions.

Another phenomenological aspect of chess expertise to be explained is the speed with which chess masters access information about adequate plans and position evaluation, and why, according to De Groot (1946/1978), they literally "see" the next move. No search, no application of an evaluation function is needed for a first approximation, and this automatic process is sufficient enough to play a most reasonable game in speed chess or simultaneous games against weaker players (Calderwood, Klein, & Crandall, 1988; Gobet & Simon, in press-a). Of course, playing a game at a professional level requires more than a first approximation and asks for deep search and subtle evaluations of the positions reached during this search. Although all four theories address this question by supposing that information in LTM is accessed, only the chunking and template theories specify mechanisms allowing this rapid access.

As chess players' main occupation is not to perform recall experiments but to play chess, it is important to address the role of chunks, templates, and retrieval structures during the choice of a move task. Chase and Simon (1973b) proposed that chunks act as conditions of productions and that they are linked to instructions allowing the mind's eye, where search is carried out, to construct structures isomorphic to them. In addition to the roles ascribed by Chase and Simon to chunks, templates can be used in several other ways (Gobet, 1995). First, they provide relevant information on the position at hand (goals, plans, moves, tactical motives, and so on...). Second, as pattern recognition is used recursively during search, they provide information on some positions reached during look-ahead. Third, they allow abstract search in a schemata space, not only in a move space. Finally, the retrieval structure aspect of the template allows rapid correcting of some values of the schema during look-ahead.

With respect to retrieval structures, Ericsson and Kintsch (1995) suggested that they are necessary to explain how strong players can accurately and rapidly represent changing positions when looking ahead or when playing blindfold.

5. DISCUSSION

It is now time to summarize, for each theory, the positive and negative evidence. The reader is referred to the discussion at the end of each set of empirical data for details on the application of each theory.

The chunking theory does better than is advertised in the literature. The reason is that most criticisms were aimed at the computer model MAPP (Simon & Gilmartin, 1973), which implemented only a subset of the chunking theory. Since all alternative theories but the template theory do not provide one with a detailed model, comparison of the verbal exposition of the theory, as done in this paper, seems fairer. The basic ideas (chunks are the units of perceptual learning, and it takes several seconds to create one of them) account for many results: recall with brief presentation time (even below 1 s); recall of game and random positions, as well as positions taken from actual and random games; dominant role of visuo-spatial encoding; and differential recall of positions modified by mirror image or by translation. Strong empirical evidence was also gained from studies aimed at identifying chunks. Assuming that chunks give access to a schematic semantic LTM (as mentioned, but not worked out in detail, by Chase and Simon, 1973b), the chunking theory accounts for the role of semantic orientation as well. The theory does not say much about typicality and seems weak with respect to the interference studies (in particular with the multiple-board task) and high-level descriptions reported by masters, though additional assumptions on subjects' strategies and on the size of chunks may salvage it in these cases. With respect to problem solving, it proposes that chunks are unpacked in the mind's eye, which allows a rapid access to the information for a short period of time. The brevity of this storage is compatible with the phenomena of progressive deepening. Finally, the simulations reported in De Groot and Gobet (in press) were obtained with essentially a chunking model.

Knowledge-based theories are harder to judge, because they are left largely unspecified. Intuitively, they capture the high-level description reported by masters, allowing them to give some explanation for the interference studies and the roles of semantic orientation and of typicality. As they do not presuppose any rapid LTM encoding, they seem compatible with progressive deepening. Their weaknesses are with the recall of very briefly presented positions, with random positions, and with the effect of board modification. Finally, they do not say much about short-range learning.

The long-term working memory theory shares many of the difficulties shown by the knowledge-based theories, in part because, as in the latter theories, many aspects are not specified. Some data are not clearly handled by the theory, including recall of briefly presented positions, interference studies, and short-range learning. Other data are directly at variance with the predictions of the theory. Ericsson and Kintsch (1995, p. 237) stress that "The ability to store random chess positions provides particularly strong evidence for the ability to encode individual chess pieces into the retrieval structure." The empirical data clearly refute this claim: with the recall of random positions, masters perform poorly with a presentation of 5 s (one third of the pieces correct), and even with a presentation of 60 s, they do not recall more than two thirds of the pieces correctly (both with visual and auditory presentation). The recall of random illegal games brings their recall of piece locations close to that of weak players. It is clear that masters take no benefit of a retrieval structure with such positions. Another negative piece of evidence is offered by the fact that masters do not reach perfect recall with positions having only a few pieces on the board ("endgames"), and by the differential recall of positions modified by mirror image and by translation. Perhaps, the theory fares best with its explanation of the rapid access shown by masters to the piece location within a position. Finally, it is unclear, from the point of view of this theory, why masters, when trying to reach a node already met in the search space, need to mentally play the moves leading to it and do not reach it directly.

In a sense, the template theory takes the best of each of the previous theories; hence, it is not surprising that it accounts for most of the data reviewed. The concept of chunks accounts for the recall of game and random positions, as well as positions from game and random games, for the dominant role of visuo-spatial encoding, and for the differential recall of positions modified by mirror image or by translation. It also accounts, with additional assumptions reviewed earlier, for eye movements. The concept of templates, which is a mixture of the concepts of high-level description, chunks, and retrieval structure, is the key for explaining the interference and multiple-board results and the role of presentation time on recall of game positions. Since templates (and chunks) are connected to other nodes in semantic LTM memory, they account for the effects of semantic orientation and typicality. Finally, because the encoding power of the template is weaker than that of the retrieval structure proposed by Ericsson and Kintsch (1995), it does not encounter the same problems with progressive deepening. Note that, in the current stage of the theory, little is said of the recognition experiments (perhaps this could be addressed by some LTM activation mechanism).

Admittedly, the template theory and the retrieval structure theory share many aspects: rapid encoding into LTM, importance of retrieval cues, short capacity of STM. The main difference between the two theories is illustrated by Ericsson and Kintsch's (1995) Figure 4. In the long-term working memory approach, encoding through retrieval cues occurs before schemata in LTM are accessed; a generic retrieval structure is postulated. In the template approach, encoding into slots occurs after a schema has been accessed through perceptual cues. Templates offer partial retrieval structures that are specific to a class of positions. These two differences—specificity vs. generality of the retrieval structure, and partial vs. total ability of the structure to encode information—explain why one theory accounts successfully for most of the results reviewed here, and why the other fails (Gobet, 1996). While the general message of Ericsson and Kintsch—that encoding into LTM is faster than was supposed in earlier models—may be valid, the general mechanism they propose does not apply to the wide range of domains they claim it does. It is not the case that general-purpose retrieval structures develop within all domains of expertise, in particular in domains where there is no deliberate attempt to improve one's memory. The concept of retrieval structure seems to offer a theoretically plausible explanation mostly in domains where memory for order is important, where there is a conscious effort to both construct and use a memory structure under strategical control, and where the input is encoded serially. Chess, which offers a bidimensional structure where reliance on the order of encoding is not important, and which is a domain where memory of positions is not an primordial goal, does not fit this description, nor do many (most?) other domains of expertise. (Note that Ericsson and Kintsch's treatment of text comprehension does not presuppose the presence of a general-purpose retrieval structure and seems compatible with the template theory.)

In addition to accounting for most of the empirical data on chess memory, the template theory, as did the chunking theory, offers a comprehensive theory of expertise, including problem solving, perception, and memory. It is embodied as a computer program, which permits precise tests of the theory to be carried out. While the generality of this theory outside the realm of chess has yet to be established, its kinship with the successful chunking theory indicates that its prospects are good. In addition, it is compatible with EPAM IV (Richman, Staszewski & Simon, 1995), which has recently been used to simulate the behavior of a mnemonist specialized in the digit-span task, one of the tasks which has led to the development of the skilled memory theory (Chase & Ericsson, 1982).

While Binet (1894, 1966) was quite enthusiastic about his results on skilled mental calculators, he could not help display a clear pessimism for our understanding of the chess players' mind. This judgment was justified both by a lack of theoretical structure and by a poverty of experimental tools allowing him to measure chess players' abilities. One hundred years after, Binet's pessimism can be overcome: as discussed in this paper, numerous and refined empirical techniques have been developed within cognitive psychology to explore the chess player's mind, and the impact of chess research on the study of expertise in particular and on cognitive psychology in general is important. The main features of chess expertise (selective search, memory for meaningful material in the domain of expertise, importance of pattern recognition) have been shown to be generalizable to other domains. As shown in this paper, chess offers a rich database of empirical results that allows for testing theories of expert memory rigorously. In addition, built on previous information-processing models, a far-ranging and consistent theory of chess players' memory is now available, which offers a promising framework both for developing a complete model of chess expertise, including problem solving, and for unifying the vast body of experimental results within the study of expertise in general.

6. REFERENCES

Allard, F., Graham, S. & Paarsalu, M. E. (1980). Perception in sport: Basketball. *Journal of Sport Psychology*, *2*, 22-30.

Baddeley, A. (1986). *Working memory*. Oxford: Clarendon Press.

Binet, A. (1894). *Psychologie des grands calculateurs et joueurs d'échecs*. Paris: Hachette. [Reedited by Slatkine Ressources, Paris, 1981.]

Binet, A. (1966). Mnemonic virtuosity: A study of chess players. *Genetic Psychology Monographs, 74,* 127-162. Translated fom the *Revue des Deux Mondes (1893), 117,* 826-859.

Bradley, A., Hudson, S. R., Robbins, T. and Baddeley, A. (1987). *Working memory in chess*. Unpublished report, Cambridge, May.

Brooks, R. L. (1967). The suppression of visualization in reading. *Journal of Experimental Psychology*, *19*, 289-299.

Brown, J. (1958). Some test of decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, *10*, 12-21.

Bushke, A. (1971). Alekhine blindfold. *Chess Life and Review*, *26*, 521-522.

Calderwood, B., Klein, G. A., & Crandall, B. W. (1988). Time pressure, skill, and move quality in chess. *American Journal of Psychology, 101,* 481-493.

Charness, N. (1974). *Memory for chess positions: The effects of interference and input modality*. Unpublished doctoral dissertation, Carnegie Mellon University.

Charness, N. (1976). Memory for chess positions: Resistance to interference. *Journal of Experimental Psychology: Human Learning and Memory*, *2*, 641-653.

Charness, N. (1979). Components of skill in bridge. *Canadian Journal of Psychology, 33*, 1-16.

Charness, N. (1981a). Search in chess: Age and Skill differences. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 467-476.

Charness, N. (1981b). Visual short-term memory and aging in chess players. *Journal of Gerontology*, *36*, 615-619.

Charness, N. (1989). Expertise in chess and bridge. In D. Klahr & K. Kotovsky (Eds.), *Complex Information processing, the impact of Herbert A. Simon.* Hillsdale, NJ: Lawrence Erlbaum Ass.

Charness, N. (1992). The impact of chess research on cognitive science. *Psychological Research, 54,* 4-9.

Charness, N., and Reingold, E. (1992, July). *Eye Movements Studies of Problem Solving in Chess.* Paper presented at the International Congress of Psychology, Brussels, Belgium.

Chase, W. G., & Ericsson, K. A. (1982). Skill and working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 16). New York: Academic Press.

Chase, W. G., & Simon, H. A. (1973a). Perception in Chess. *Cognitive Psychology*, *4*, 55-81.

Chase, W. G., & Simon, H. A. (1973b). The mind's eye in chess. In W. G. Chase (Ed.) *Visual information processing*. New York: Academic Press.

Chi, M. T. H. (1978). Knowledge structures and memory development. In R. S. Siegler (Ed.), *Children's thinking: What develops?*, Hillsdale, N.J.: Erlbaum.

Cleveland, A. A. (1907). The Psychology of Chess and of Learning to play it. *The American Journal of Psychology*, *XVIII*, 269-308.

Cooke, N.J., Atlas, R. S., Lane, D.M. and Berger, R. C. (1993). Role of high-level knowledge in memory for chess positions. *American Journal of Psychology, 106*, 321-351.

Craik, F. I. M. & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*, 671-681.

Cranberg, L. & Albert, M. L. (1988). The chess mind. In Obler L. K. & Fein D. (Eds.), *The exceptional brain. Neuropsychology of talent and special abilities*. New York : Guilford press.

de Groot, A. D. (1946). *Het denken van den schaker*. Amsterdam, Noord Hollandsche.

de Groot, A. D. (1966). Perception and Memory Versus Thought: Some Old Ideas and Recent Findings. In B. Kleinmuntz (Ed.), *Problem Solving, Research, Method and Theory*. New York: Krieger, 1966.
de Groot, A. D. (1978). *Thought and Choice in Chess* (2nd Ed.). The Hague: Mouton Publishers.
de Groot, A. D., & Gobet, F. (in press). *Perception and memory in chess. Heuristics of the professional eye*. Assen: Van Gorcum.
de Groot, A. D., & Jongman, R. W. (1966). *Heuristics in Perceptual Processes. An investigation of chess perception*. XVIII International Congress of Psychology, Moscow, p. 15-24.
Dextreit, J. & Engel, N. (1981). *Jeu d'échecs et sciences humaines*. Paris: Payot.
Djakow, I. N., Petrowski, N. W., & Rudik, P. A. (1927). *Psychologie des Schachspiels*. Berlin: de Gruyter.
Egan, D. E., & Schwartz, E. J. (1979). Chunking in recall of symbolic drawings. *Memory & Cognition*, *7*, 149-158.
Eisenstadt, M. & Kareev, Y. (1977). Perception in game playing: internal re-presentation and scanning of board positions. In P. N. Johnson-Laird & P. C. Wason (Eds.), *Thinking: Readings in Cognitive Science*. Cambridge: Cambridge University Press.
Ellis, S. H. (1973). *Structure and experience in the matching and reproduction of chess patterns*. Unpublished doctoral dissertation, Carnegie Mellon University.
Elo, A. (1978). *The rating of chess players, past and present*. New York: Arco.
Engle, R. W., & Bukstel, L. (1978). Memory processes among bridge players of differing expertise. *American Journal of Psychology*, *91*, 673-689.
Ericsson, K. A., & Harris M. S. (1990, November). *Expert Chess Memory Without Chess Knowledge: A Training Study*. Paper presented at the 31st Annual Meeting of the Psychonomics Society, New Orleans.
Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102*, 211-245.
Ericsson, K. A., & Oliver, W. (1984, November). *Skilled memory in blindfolded chess.* Paper presented at the annual meeting of the Psychonomic Society, San Antonio, TX.
Ericsson, K. A., & Polson, P. G. (1988). A cognitive analysis of exceptional memory for restaurant orders. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The Nature of Expertise*. Hillsdale, NJ: Erlbaum.
Ericsson, K. A., & Staszewski, J. J. (1989). Skilled memory and expertise: mechanisms of exceptional performance. In D. Klahr. & K. Kotovsky (Eds.), *Complex information processing: The impact of Herbert A. Simon.* Hillsdale, NJ: Erlbaum.
Feigenbaum, E . A. & Simon, H. A. (1962). A Theory of the Serial Position Effect. *British Journal of Psychology, 53*, 307-320.
Feigenbaum, E. A. (1963). The simulation of verbal learning behavior. In E. A. Feigenbaum & J. Feldman (Eds.), *Computers and thought*. New York: McGraw-Hill.
Feigenbaum, E. A., & Simon, H. A. (1984). EPAM-like models of recognition and learning. *Cognitive Science, 8*, 305-336.
Fine, R. (1965). The psychology of blinfold chess: an introspective account. *Acta Psychologica*, *24*, 352-370.
Frey, P. W., & Adesman, P. (1976). Recall memory for visually presented chess positions. *Memory and Cognition*, *4*, 541-547.
Freyhoff, H., Gruber, H. & Ziegler, A. (1992). Expertise and hierarchical knowledge representation in chess. *Psychological Research, 54,* 32-37.
Gobet, F. (1993a). *Les mémoires d'un joueur d'échecs.* Fribourg: Editions Universitaires.
Gobet, F. (1993b). A computer model of chess memory. *Proceedings of 15th Annual Meeting of the Cognitive Science Society,* (pp. 463-468).
Gobet, F. (1995). *Chess thinking revisited.* Submitted for publication.

Gobet, F. (1996). *Long-Term Working Memory: Comment on Ericsson and Kintsch (1995).* Submitted for publication.
Gobet F., & Jansen, P. (1994). Towards a chess program based on a model of human memory. In H. J. van den Herik, I. S. Herschberg, & J. W.Uiterwijk (Eds.), Advances in Computer Chess 7. Maastricht: University of Limburg Press.
Gobet, F., & Simon, H. A. (1992, July). *Chess memory revisited: Recall of several boards.* Paper presented at the XXVth International Congress of Psychology, Brussels.
Gobet, F., & Simon, H. (1995a). *Role of presentation time in recall of game and random chess positions.* Submitted for publication.
Gobet, F., & Simon, H. A. (1995b). *Expert chess memory: Revisiting the chunking hypothesis*. Manuscript submitted for publication.
Gobet, F., & Simon, H. A. (in press-a). The Roles of recognition processes and look-ahead search in time-constrained expert problem solving: Evidence from grandmaster level chess. *Psychological Science.*
Gobet, F., & Simon, H. A. (in press-b). Templates in chess memory: A mechanism for recalling several boards. *Cognitive Psychology.*
Gobet, F., & Simon, H. A. (in press-c). Recall of random and distorted positions: Implications for the theory of expertise. *Memory & Cognition.*
Gobet, F., & Simon, H. A. (in press-d). Recall of rapidly presented random chess positions is a function of skill. *Psychonomic Bulletin & Review.*
Gobet, F., Richman, H., & Simon, H. A. (in preparation). Chess players' memory and perception: a unified process model.
Gold, A. & Opwis, K. (1992). Methoden zur empirischen Analyse von Chunks beim Reproduzieren von Schachstellungen. *Sprache & Kognition, 11*, 1-13.
Goldin, S. E. (1978a). Memory for the Ordinary: Typicality Effects in Chess Memory, *Journal of Experimental Psychology: Human Learning and Memory*, *4*, 605-616.
Goldin, S. E. (1978b). Effects of orienting tasks on recognition of chess positions. *American Journal of Psychology*, *91*, 659-671.
Goldin, S. E. (1979). Recognition memory for chess positions: Some preliminary research. *American Journal of Psychology*, *92*, 19-31.
Gruber, H. & Strube, G. (1989). Zweierlei Experten : Problemisten, Partiespieler und Novizen bei Lösen von Schachproblemen. *Sprache & Kognition, 8,* 72-85.
Gruber, H. (1991). *Qualitative Aspekte von Expertise im Schach.* Aachen: Feenschach.
Gruber, H., & Ziegler, A. (1990). Expertisegrad und Wissensbasis. Eine Untersuchung bei Schachspielern. *Psychologische Beiträge, 32*, 163-185.
Hartston, W. R. & Wason, P. C. (1983). *The psychology of chess*. London: Batsford.
Holding, D. H. (1985). *The psychology of chess skill.* Hillsdale, NJ: Erlbaum.
Holding, D. H. (1992). Theories of chess skill. *Psychological Research, 54,* 10-16.
Holding, D. H., & Reynolds, R. I. (1982). Recall or evaluation of chess positions as determinants of chess skill. *Memory and Cognition*, *10*, 237-242.
Horgan, D. D., & Morgan, D. (1990). Chess expertise in children. *Applied Cognitive Psychology*, *4*, 109-128.
Jongman, R. W. (1968). *Het oog van de meester*. Amsterdam: Van Gorcum.
Kintsch, W. (1970). Models for free recall and recognition. In D. A. Norman, (Ed.), *Models of human memory*. New York: Academic Press.
Kovacevic, M. (1985). *Kognitivi Processi v Sahu.* (Cognitive Processes in Chess). Unpublished Diploma Thesis, Filozofski Fakultet v Beogradu.
Lane, D. M., & Robertson, L. (1979). The generality of the levels of processing hypothesis: An application to memory for chess positions. *Memory and Cognition*, *7*, 253-256.
Larkin, J. H., & Simon, H. A. (1987). Why a Diagram Is (Sometimes) Worth Ten Thousands Words. *Cognitive Science*, *11*, 65-99.

Lories, G. (1984). La mémoire des joueurs d'échecs (revue critique). *L'Année Psychologique*, *84*, 95-122.
Lories, G. (1987). Recall of random and non random chess positions in strong and weak chess players. *Psychologica Belgica*, *27*, 153-159.
Mc Keithen, K. B., Reitman, J. S., Rueter, H. H., & Hirtle, S.C. (1981). Knowledge organisation and skill differences in computer programmer. *Cognitive Psychology, 13*, 307-325.
Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97.
Newell, A., & Simon, H. A. (1972). *Human Problem Solving*. Englewood Cliffs, NJ: Prentice-Hall.
Peterson, L. R. & Peterson, M. (1959). Short-term retention of individual items. *Journal of Experimental Psychology*, *58*, 193-198.
Pfau, H. D., & Murphy, M. D. (1988). Role of verbal knowledge in chess. *American Journal of Psychology, 101,* 73-86.
Reitman, J. S. (1976). Skilled perception in go: deducing memory structures from inter-response times. *Cognitive Psychology, 8*, 336-356.
Reynolds, R. I. (1982). Search heuristics of chess players of different calibers. *American Journal of Psychology*, *95*, 383-392.
Richman, H. B., & Simon, H. A. (1989). Context effects in letter perception: Comparison of two theories. *Psychological Review*, *96*, 417-432.
Richman, H. B., Simon, H. A. & Gobet, F. (1991, July). Applying retrieval structures to chess memory. Paper presented at the International conference on memory, Lancaster.
Richman, H. B., Staszewski, J., & Simon, H. A. (1995). Simulation of expert memory with EPAM IV. *Psychological Review, 102*, 305-330.
Rosch, E. H. (1973). On the internal structure of perceptual and semantic categories. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* . New York: Academic Press.
Saariluoma, P. (1984). *Coding problem spaces in chess: A psychological study.* Commentationes scientiarum socialium 23. Turku: Societas Scientiarum Fennica.
Saariluoma, P. (1985). Chess players' intake of task-relevant cues. *Memory & Cognition*, *13*, 385-391.
Saariluoma, P. (1989). Chess players' recall of auditorily presented chess positions. *European Journal of Cognitive Psychology*, *1*, 309-320.
Saariluoma, P. (1990). Apperception and restructuring in chess players problem solving. In K. J. Gilhooly, M. T. G. Keane, R.H. Logie, and G. Erdos (Eds.) *Lines of thinking* (Volume II). New York: Wiley.
Saariluoma, P. (1991). Aspects of skilled imagery in blinfold chess. *Acta psychologica, 77*, 65-89.
Saariluoma, P. (1992). Visuospatial and articulatory interference in chess players' information intake. *Applied Cognitive Psychology*, *6* , 77-89.
Saariluoma, P. (1994). Location coding in chess. *The Quarterly Journal of Experimental Psychology, 47A,* 607-630.
Selz, O. (1922). *Zur Psychologie des produktiven Denkens und des Irrtums*. Bonn: Friedrich Cohen.
Shneiderman, B. (1976). Exploratory experiments in programmer behavior. *International Journal of Computer and Information Sciences*, *5*, 123-143.
Simon, H. A. (1976). The information-storage system called "human memory." In M. R. Rosenzweig, & E. L. Bennet (Eds.), *Neural Mechanisms of Learning and Memory*. Cambridge, Mass: MIT Press.
Simon, H. A., & Barenfeld, M. (1969). Information processing analysis of perceptual processes in problem solving. *Psychological Review*, *76*, 473-483.
Simon, H. A., & Chase, W. G. (1973). Skill in Chess, *American Scientist*, *61*, 393-403.
Simon, H. A., & Gilmartin, K. J. (1973). A simulation of memory for chess positions. *Cognitive Psychology*, 5, 29-46.

Sloboda, J. A. (1976). Visual perception of musical notation: Registering pitch symbols in memory. *Quarterly Journal of Experimental Psychology*, *28*, 1-16.
Staszewski, J. J. (1988). Skilled memory and expert mental calculation. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The Nature of Expertise*. Hillsdale, NJ: Erlbaum.
Staszewski, J. J. (1990). Exceptional memory : The influence of practice and knowledge on the development of elaborative encoding strategies. In W. Schneider & F. E. Weinert (Eds.), *Interactions among aptitudes, strategies, and knowledge in cognitive performance* (pp. 252-285). New York : Springer.
Thurstone, L. L. (1930). The relation between learning time and length of task. *Psychological Review*, *37*, 44-48.
Vicente, K. J., & de Groot, A. D. (1990). The Memory Recall Paradigm: Straightening Out the Historical Record, *American Psychologist,* February, 285-287.
Vicente, K. J., & Wang, J. H. (1995). An ecological theory of expertise effects in memory recall. University of Toronto, Department of Industrial Ingineering, CEL 95-01.
Watkins, M. J., Schwartz, D. R., & Lane, D. M. (1984). Does part-set cueing test for memory organization? Evidence from reconstruction of chess positions. *Canadian Journal of Psychology, 38,* 498-503.

ACKNOWLEDGEMENTS

Preparation of this article was supported by grant No. 8210-30606 from the Swiss National Funds of Scientific Research and by Grant No. DBS-9121027 to H. A. Simon from the American National Science Foundation. Correspondence concerning this article should be addressed to Fernand Gobet, Department of Psychology, University of Nottingham, University Park, Nottingham NG7 2RD, England.

The author thanks Neil Charness, Adriaan de Groot, Howard Richman, Herbert Simon, Jim Staszewski, Shmuel Ur, and one anonymous reviewer for valuable comments on a first draft of this manuscript.