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Expert Memory: A Comparison of Four Theories

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Running head: Expert Memory

Abstract

This paper compares four current theories of expertise with respect to chess players' memory: Chase and Simon's (1973) chunking theory, Holding's (1985) SEEK theory, Ericsson and Kintsch's (1995) long-term working memory theory, and Gobet and Simon's (1996b) template theory. The empirical areas showing the largest discriminative power include recall of random and distorted positions, recall with very short presentation times, and interference studies. Contrary to recurrent criticisms in the literature, it is shown that the chunking theory is consistent with most of the data. However, the best performance in accounting for the empirical evidence is obtained by the template theory. The theory, which unifies low-level aspects of cognition, such as chunks, with high-level aspects, such as schematic knowledge and planning, proposes that chunks are accessed through a discrimination net, where simple perceptual features are tested, and that they can evolve into more complex data structures (templates) specific to classes of positions. Implications for the study of expertise in general include the need for detailed process models of expert behavior and the need to use empirical data spanning the traditional boundaries of perception, memory, and problem solving.

Expert Memory: A 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, 1966) monograph on the psychology of skilled mental calculators and chessplayers (see Bryan & Harter, 1899, Cleveland, 1907, or Djakow, Petrowski and Rudik, 1927 for other early examples). Recently, cognitive science has produced a wealth of empirical data on expertise, and several theoretical explanations 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 timely then 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. Chess, with its long tradition in scientific psychology, its rich database of observational and experimental data, and the presence of several detailed theories, some of them implemented as computer programs, appears as a domain of choice to carry out such a theoretical comparison.

The first section of this paper emphasizes the scientific advantages offered by the study of chess players. The second section presents three leading approaches to studying expertise: the chunking theory (Chase & Simon, 1973b), the knowledge-based paradigm (e.g., Chi, Glaser, and Rees, 1982), and the skilled-memory theory (Chase & Ericsson, 1982), which has recently been extended in the long-term working memory (LT-WM) theory (Ericsson & Kintsch, 1995). The third section shows how these approaches to expertise have been applied to chess memory. Four theories are presented: Chase and Simon's (1973b) chunking theory and Ericsson and Kintsch's (1995) LT-WM theory are direct applications to chess of their general theories; Holding's SEEK theory (1985, 1992) is a prime example of the knowledge approach in the domain of chess; finally, Gobet and Simon's (1996b) template theory is an

elaboration of the chunking theory and includes concepts derived both from the skilled-memory theory and the knowledge-based paradigm. In the fourth section, these four theories are set against empirical work conducted during the last twenty years or so on chess memory. In the conclusion, the respective explanatory power of these theories for chess memory is discussed, and implications are drawn for the study of expertise in general.

The reader who has come across several reviews of chess expertise in recent years (e.g., Charness, 1989, 1992; Cranberg & Albert, 1988; Gobet, 1993a; 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, 1996; Gobet & Simon, 1996b, 1996c; Saariluoma, 1992, 1994), as well as a rebuttal of a widely cited result about the lack of skill effect in the recall of random positions (Gobet & Simon, 1996a). Second, two new theories (Ericsson & Kintsch, 1995; Gobet & Simon, 1996b) 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 test of empirical data.

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 a domain of comparison, and to estimate how the conclusions of this comparison 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 science. Its impact on cognitive science in general is important (Charness, 1992) for several reasons (see Gobet, 1993a, for a more detailed discussion): (a) the chess domain offers strong external validity; (b) it also offers strong ecological validity (Neisser, 1976); (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 that 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.

The first point mentioned, external validity, is obviously an essential prerequisite if one wants to go beyond the limits of a specific domain. Chess fares well on that point: the basic result of De Groot (1946/1965) and Chase and Simon (1973a, 1973b)—experts' superiority over novices with meaningful material in their domain of expertise—has been replicated in different domains, such as GO and gomoku (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).

Current Approaches to Expertise

Research on expertise has been one of the most active fields of cognitive science over the last two decades (Patel, Kaufman, & Magder, 1996). A huge amount of empirical data has been collected in various domains, including physics, mathematics, chess, baseball, golf, medical expertise, to name only a few (see Ericsson & Lehman, 1996, for a review). In addition, several influential paradigms have been proposed to account for expert behavior, including Soar (Newell, 1990), ACT* (Anderson, 1983), Chase and Simon's (1973b) chunking theory, Chase and Ericsson's (1982) skilled memory theory and its successor Ericsson and Kintsch's (1995) long-term working memory theory, and what can be called the "knowledge-based paradigm," which incorporates a group of authors mainly stressing the necessity of a well organized database of knowledge. In this paper, I will focus on the last three of these paradigms.

The Chunking Theory

The chunking theory (Chase and Simon, 1973) is indissociable from EPAM (Feigenbaum, 1963; Feigenbaum & Simon, 1984; Simon, 1989; Richman & Simon, 1989), a general theory of cognition. It proposes that expertise in a domain is acquired by learning a large database of chunks, indexed by a

discrimination net, where tests are carried out about features of the perceptual stimuli. The discrimination net allows a rapid categorization of domain-specific patterns and accounts for the speed with which experts “see” the key elements in a problem situation. The theory incorporates several parameters specifying known limits of the human information-processing system, such as short-term memory capacity (about 7 chunks), time to carry out a test in the discrimination net (10 ms), or time to learn a new chunk (about 8 s).

Chunks also play the role of conditions of productions (Newell & Simon, 1972): each familiar chunk in LTM is a condition that may be satisfied by the recognition of the perceptual pattern and that evokes an action. Productions explain the rapid solutions that experts typically propose and offer a theoretical account of “intuition” (Simon, 1986). The fact that experts in many domains (e.g., physics, Larkin, McDermott, Simon, & Simon, 1980; chess, De Groot, 1946; mathematics, Hinsley, Hayes, & Simon, 1977) use forward search when solving a problem, while novices work backwards, is taken as evidence that experts make heavy use of productions based on pattern recognition. Chunks also give access to semantic memory consisting of productions and schemas, although this aspect of the theory is less worked out (Simon, 1989).

The presence of chunks also explains why, notwithstanding the limits of STM, experts can recall larger amounts of information than novices: instead of storing each element separately in STM, experts can store chunks that have been built up in LTM. Finally, the theory postulates that it takes a long time (at least 10 years of practice and study) to learn the large amount of chunks (from 10,000 to 100,000) necessary to be an expert. It is fair to say that this theory has spawned most of the current work on expertise, carried out not in small part to refute some of its predictions.

The Knowledge-Based Paradigm

The second theoretical framework—it is not possible to pinpoint a specific theory as in the two other cases—stresses the role of high-level, conceptual knowledge, sometimes referring to the levels-of-processing theory (Craik & Lockhart, 1972). From this point of view, experts differ not only in the quantitative amount of knowledge (as proposed by Chase & Simon, 1973), but also in its qualitative organization. For example, Chi, Glaser, and Rees (1982) showed that experts organize physics problems at a more abstract level than

novices, who pay attention mostly to surface features. Typically, experts' knowledge is organized hierarchically. Similar qualitative differences have been found in other domains, such as medical expertise (Patel & Groen, 1991), programming (Adelson, 1984), or chess (Cooke et al., 1993). It was also shown that the type of knowledge representation used influences the flexibility with which problems are represented (Larkin, McDermott, Simon, & Simon, 1980) and the type of search used (Bhaskar & Simon, 1977).

Several formalisms have been used to model experts knowledge—and knowledge in general, for that matter— including production systems (Larkin, 1981), semantic networks (Rumelhart, Lindsay, & Norman, 1972), frames (Minsky, 1977), and trees (Reitman & Rueter, 1980). [See Reitman-Olson and Biolsi (1991) for a useful review of techniques used for eliciting and representing knowledge.] Finally, empirical work has also validated some of the assumptions of this framework. An important source of evidence for this approach comes from the engineering field of expert systems (e.g., Jackson, 1990), where computer programs are written to represent and use experts' knowledge at levels of performance close to humans'. While this paradigm could, in principle, coexist with the chunking theory, as proposed by Simon and his colleagues, it has mostly evolved in an independent direction.

The Skilled-Memory and Long-Term Working Memory Theories

As we will see later with respect to chess memory, two sets of empirical data are hard to account for by the chunking theory: (a) Experts keep a good memory for domain-specific material even after a task has been interpolated between the presentation of the material and its recall; and (b) Experts can memorize large amounts of rapidly presented material that would either require learning chunks faster than is proposed by the theory or a STM capacity larger than 7 chunks. The skilled memory theory (Chase & Ericsson, 1982; Ericsson & Staszewski, 1989; Staszewski, 1990) precisely addresses these two questions, mostly using data from the digit-span task, and explains experts' remarkable memory in various domains through three principles: (a) Information is encoded with numerous and elaborated cues related to prior knowledge; (b) Time required by encoding and retrieval operations decreases with practice; and (c) Retrieval structures are developed. According to Ericsson and Staszewski (1989, p. 239), "experts develop memory mechanisms called

retrieval structures to facilitate the retrieval of information stored in LTM. [...] [R]etrieval structures are used strategically to encode information in LTM with cues that can be later regenerated to retrieve the stored information efficiently without a lengthy search.”

This approach has been applied mainly to mnemonists, though it has also been 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 (retrieval cues) are made between the locations and the items to be learnt. 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.

 Insert Figure 1 about here

Recently, Ericsson and Kintsch (1995) have extended the skilled memory theory into the long-term working memory (LT-WM) theory. 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. Depending upon the requirements of the task domain, 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 (see Figure 1).² The former type of encoding predicts that, due to the presence of retrieval cues, relatively good recall should be observed even when the presentation time was not sufficient for elaborating LTM schemas. Note that the LT-WM theory proposes that working memory has a larger capacity than is traditionally proposed, for example by Baddeley and Hitch's (Baddeley, 1986) working memory theory. Ericsson and Kintsch applied their theory to digit-span

memory, memory for menu orders, mental multiplication, mental abacus calculation, chess, medical expertise, and text comprehension.

Current Theories of Expert Memory in Chess

This section presents four current theories that have been proposed to account for expert memory in general and chessplayers' memory in particular. The first three theories instantiate the general theories of expertise discussed above; the last theory proposes an integration of these three approaches, building particularly from chunking theory. Each will be illustrated by giving its explanation for the standard chess memory task (recall of a game position presented for 5 s).

The Chunking Theory

Chase and Simon's theory was so influenced by De Groot's (1946/1965) experimental and theoretical work on chess psychology that it may be worth dwelling on this study for a while. This will also provide the opportunity to present the typical experimental paradigm of chess research.

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 so on) and also for his demonstration that level of chess skill dramatically affects the recall of positions shown for a short amount of time.

De Groot's memory experiment, which set up the program for much later experimental work in the field, 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 s). The position is then removed from their sight, and subjects 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 remembered the position almost perfectly after a presentation ranging from 2 to 5 s (an average of 93% pieces correct), while his weakest subject, the equivalent of a class A player, barely got 50% correct.³ Moreover, protocols show that strong players grasp 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, 1965, De Groot & Gobet, 1996).

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, 1996) 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 conditions to reach mastership include (a) a schooled and highly specific mode of perception, and (b) a system of methods stored in memory and rapidly accessible. 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.

Chase and Simon (1973b) re-investigated De Groot’s (1946/1965) 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 Gilmarin (1973) described a computer model (MAPP) that implemented a subset of the chunking theory and simulated the memory processes of chess players. MAPP combined elements of PERCEIVER (Simon & Barenfeld, 1969) and of EPAM. As illustrated by Figure 2, the 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). MAPP implemented STM as encoding a set of patterns without semantic or ordered relation to each other. In essence, this model 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 model was that the same cognitive limitations (e.g., STM capacity, encoding rate into LTM) apply in chess memory as in other cognitive domains.

 Insert Figure 2 about here

When used as a 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 stored in LTM (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. 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.

The mind's-eye model acts as a production system (Newell & Simon, 1972): chunks are automatically activated by the constellations on the external chessboard and trigger potential moves that will then be placed in 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.

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, 1996).

The SEEK Theory

Several knowledge-based explanations have been proposed to remedy the (sometimes presumed) weaknesses of the chunking theory. For example, it has been emphasized that masters recall a corrected version of a prototype (Hartston & Wason 1983), re-categorize chunks in order to achieve a global characterization of the position (Lories, 1984), access deeper semantic codes (e.g., Goldin, 1978; Lane & Robertson, 1979), or make use of high-level verbal knowledge (Cooke et al., 1993; Pfau & Murphy, 1988). But perhaps the most developed example of a knowledge-base theory for chess expertise—although many aspects of it are rather underspecified—is Holding's (1985, 1992) SEEK (SEarch, Evaluation, Knowledge) theory. This choice is also apt because Holding explicitly rejects mechanisms similar to those proposed by the chunking theory.

SEEK proposes that three elements play a key role in chess expertise: search, evaluation, and knowledge. Masters play better than weaker players because they search more and better, because they evaluate the terminal positions in their search better, and because they know more. According to Holding, evaluation, and search to some extent, are made possible by the presence of an extensive knowledge base. The organization of this knowledge is more complex than proposed by the chunking theory, and allows experts to store the “gist” of a position, instead of its perceptual layout. Working memory is used in several ways in the theory: to store moves that have been explored, to remember the evaluation of a line, or to keep a trace of previous games that may be useful as guidelines. Holding (1985, p. 251) specifically notes that chunk recognition is not necessary, since general characteristics of the positions may be used to generate the necessary knowledge.

SEEK explains masters' outstanding recall of briefly-presented position by the greater familiarity they have with chess positions. This familiarity allows them “to classify a new position as a set of interlocking common themes, or as

a set of deviations from prototype in long-term memory, while committing very little to rote memory” (Holding, 1985, p. 249). Holding also stressed that chess masters’ memories are rich and highly organized and that they are more general than specific, contrary to what is proposed by the chunking theory. The part of chess knowledge that is specific consists of the verbal encoding of sequences of moves. Finally, part of chess (meta)knowledge consists of principles for efficient search (for example, when to stop searching a line) and adequate evaluation. These principles are crucial in acquiring expertise, and most of them are encoded verbally. On one point Holding agrees with Chase and Simon, namely that a large amount of time and effort are necessary to acquire the skills of a chess master.

Although the SEEK theory has often been assumed to account for chess expertise in general and chess memory in particular, it has never been systematically subjected to empirical test. Moreover, its exposition is verbal, and its mechanisms (in particular with respect to memory phenomena) are not sufficiently detailed to allow the construction of a workable model. As will be seen later, it is often impossible to use SEEK without adding numerous *ad hoc* hypotheses.

The Long-Term Working Memory Theory

In the case of chess expertise, the LT-WM 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 to each other and associates pieces to their corresponding locations, allows a rapid encoding into LTM. In addition to the retrieval structure, it is proposed that chess experts encode information by elaborating LTM schemas. (Figure 1 describes the application of LT-WM theory for serial stimuli. To visualize its application to chess, a bi-dimensional domain, simply add a second dimension to the portion of the Figure depicting the hierarchical organization of retrieval cues.)

As noted elsewhere (Gobet, 1997), the LT-WM theory is rather vague (e.g., what is the exact nature of the hierarchical retrieval structure?) and under-specified (no time parameters are specified for encoding information into the retrieval structure and for elaborating LTM schemas). This allows for (at least)

two interpretations, depending on whether information encoding at higher levels of the retrieval structure is contingent upon encoding at lower levels. The square interpretation takes Ericsson's and Kintsch (1995) description literally (e.g.: "If, on the one hand, chess experts had a retrieval structure corresponding to a mental chess board, they could store each piece at a time at the appropriate location within the retrieval structure." p. 237; emphasis added), and assumes contingent encoding. It therefore states that most encoding relates to storing pieces in squares of the retrieval structure. The hierarchy interpretation assumes that encoding is not contingent and states that in preference to storing pieces in squares, experts store schemas and patterns in the various levels of the retrieval structure. This interpretation is compatible with Ericsson and Kintsch's general presentation of their LT-WM theory, but is not specifically backed up by their discussion of chess expertise.

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 can also be used successfully with short presentation times, as in the standard five-second presentation of a game position (Ericsson & Staszewski, 1989). The square interpretation of the theory implies 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 ms (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). The hierarchy interpretation (schemas and patterns are encoded) does not run into this problem, but has the disadvantage that the idea of retrieval structure loses its explanatory power to the benefit of a pattern-recognition based explanation—if large schemas can be recognized, then a limited STM would be sufficient.

The Template Theory

As will be shown later, Simon and Gilmarin's MAPP, as well as other models of the EPAM family, was particularly strong in its ability to explain (chess) perception and memory at the chunk level, but weak in relating these chunks to

high-level descriptions. These high-level descriptions abound in masters' retrospective protocols (see for example De Groot, 1946/1965; De Groot & Gobet, 1996) and may help explain how, upon recognition of a position, strong chess players rapidly access 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, 1996b) 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 Gilmarin, 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 in STM,⁴ 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, the plans and moves to apply, and so on. This information is organized in a schematic form (Larkin & Simon, 1987). Two learning parameters are proposed: about 8 s to create a new node in the discrimination net, and about 1 s to add information to an existing node.

For positions that subjects have studied or played extensively, it is proposed that chunks are developed into templates. Templates, which are specific to certain types of chess positions, contain at their core a large chunk. They also possess slots that may be filled in when viewing a position, in particular for features that are not stable in these types of positions. Slots, which may have default-values, contain information on the location of certain pieces, on

potential moves to play, or on semantic information like plans, tactical and strategic features, and so on. Slots are created as a function of the number of tests below a node in the discrimination net. When the same type of information (e.g., same type of piece or same square) is tested in several branches (the minimum number of occurrences is given by a parameter), a slot is created.

The theory proposes that chunks and templates are mainly accessed by visual information, although other routes to them exist, allowing a highly redundant memory management: 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—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 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 is not limited to chess and 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 (1973b) and in Simon and Gilmartin's (1973) papers, templates and productions have to be learned, as well as pointers linking them together and linking them to chunks.

Fit of the Theories to the Empirical Evidence

Recent work on chess perception and memory is now discussed, focusing on data directly relevant to the comparison of the four theories. Data will be organized around the following themes: early perception, STM capacity and LTM encoding, modality of representation, LTM organization, and learning. The reader is invited to refer to Table 1, at the end of the paper, for a preview on how the data stack up for and against the various theories. (For a discussion of chess problem solving, see Gobet, 1997).

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 SEEK and of the LT-WM theory to explain chess expertise.

Studying eye movements, De Groot and Gobet (1996) 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, as previously found by Charness and Reingold (1992) with presentation of only one quadrant of the board, masters fixate more often on the edges of the squares than the novices, which can be taken as evidence that they fixate groups of pieces instead of individual pieces.

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 ms. Ellis used 4 x 4 square miniature chess boards and presented only common patterns of white pieces. His stronger subjects (class A players) were able to retain 6.7 pieces out of 8, and his weaker subjects (class D and below), 4.5 pieces, on average. 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 (1995) 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

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 possible even with very short presentation times. In addition, a version of CHREST (De Groot and Gobet, 1996) was able to simulate human eye movements in considerable detail.⁵ 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 theories, the data on short presentation times have some important theoretical implications. With respect to SEEK, they indicate the need to explain how high-level knowledge is rapidly accessed through visual stimuli. They also show some inadequacies of the level-of-processing account, mentioned by Holding as a possible mechanism. It is doubtful that subjects process the visual stimuli at different “levels” with presentation times of one second or less. Hence, there are vast memory differences although players of different skill levels use the same level of processing.

With respect to the LT-WM theory, these results show important deficiencies in the square interpretation (that a structure similar 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 hierarchy version of the theory, which assumes that chunks and not individual pieces are typically encoded into the retrieval structure, fares better, though there is a need for the theory to add an alternative, as yet unspecified, route to schemas that offer a faster access than the route offered by retrieval structure cues (see Figure 1).

STM Capacity and LTM Encoding

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 provided 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 in latency for 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.

Similar results were found 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 when compared with a control condition where only one board was presented. 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 (1996b), 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 s. 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 (1996b) to apply a similar mnemonic technique, who could recall, with higher than 70% average accuracy, up to 9 positions presented for 8 s each, replacing as many as 160 pieces correctly.

At first blush, these results seem squarely to refute Chase and Simon's theory. However, a noticeable result of Gobet and Simon's (1996b) study was that, when Chase and Simon's 2 s boundary technique was 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, in press, for potential explanations of this difference). If chunk size is larger than that 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 encoded into template slots rapidly, **in less than 1 s**. The presence of templates explains why the multiple board task is tractable for masters, at least **for** up to four or five boards: only one **template** per position needs to be memorized (**either by storing it STM or by encoding additional information in LTM, such as episodic cues**) in order to remember the "gist" 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 relies on STM storage and, given a sufficiently long time to create a new node in LTM (about 8 s) or to add information to an existing node (about 1 s), on LTM storage. **The U-curve found by Gobet and Simon (1996a), with the first and last positions being recalled best, support the view that both LTM and STM storage are important in this task.** However, the model does not implement (yet) the idea that templates, which are in fact an organized part of semantic LTM, receive some activation when they are accessed. This may explain how players, both in the multiple board experiment and in Charness' (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 within the EPAM architecture by Richman, Staszewski and Simon (1995).

SEEK offers two explanations to account for the interference data. The first explanation is Frey and Adelman's (1976) and Charness' (1976) depth of processing account, which proposes that, with experts, traces undergo a deep treatment that protects them against retroactive interference. The second explanation is similar to that of Cooke et al. (1994), who propose that players encode one high-level description per position. In both cases, no specific mechanisms are proposed, which makes it difficult to evaluate these proposals. Note that the explanation based on high-level descriptions can be subsumed as a special case of the template theory, where templates provide players with labels for characterizing positions.

Both versions of the LT-WM theory account for the (non-chess) interference results by assuming that strong players encode each position rapidly into the retrieval structure. This explanation does not work, however, with chess interfering material, such as in the multiple board experiment, because the theory specifically states that chess experts have a single retrieval structure (Ericsson & Staszewski, 1989). The second encoding mechanism provided by the theory, elaboration of LTM schemas and patterns, may be used to account for the data. If so, several aspects of the theory are not worked out in sufficient detail: What are the time parameters in the elaboration process? Are the elaborations subject to interference or decay? Why is there a limit of around 5 boards for most subjects? **(As suggested by a reviewer, a possible answer to the last question is that there is a form of fan effect in LTM.)**

Random Positions

Experiments on the recall of random positions are theoretically interesting, because the four theories make different predictions: the chunking and template theories predict a small advantage for experts, as experts are more likely to find chunks even in random positions; SEEK predicts no superiority for experts, as no prototype can be found with these stimuli; and the LT-WM predicts a strong superiority for experts, because they can use the retrieval structure and/or create new LTM associations to encode pieces.⁸ Experiments with short presentation times are discussed in this section; those with long presentation times are discussed in the section on short-range learning.

With a presentation time of 5 s, Chase and Simon (1973a) did not find any recall difference between their three subjects (a master, a class A player and a

beginner) with random positions. 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 (1996a), reviewing a dozen experiments where random positions were used 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 s, masters place an average of 5.5 pieces, while the weakest players—below class B—place an average of 2.6 pieces).

Thus, strong players do maintain some superiority when recalling briefly presented random positions. As discussed by Gobet and Simon (1996a), this is what is predicted both by the chunking and the template models: a large database of chunks is more likely to recognize chunks serendipitously in a random position than a small one. Simulations described in Gobet and Simon (1996c) show that larger nets do indeed perform better at recalling random positions than smaller nets. Holding (1985) proposes that familiarity with chess positions plays a key role in chess players' memory, but it is unclear how SEEK's two main "mechanisms" implementing familiarity can account for the skill effect in the recall of random positions. On the one hand, high-level descriptions (or prototypes) are useless, because random positions, by construction, do not map to such high-level descriptions. On the other hand, the level-of-processing approach is at a loss with 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 square version of the LT-WM theory, which suggests that each slot in the 64-square 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 actually found. As mentioned above, even masters recall only an average of 5.5 pieces with a presentation of 5 s. The hierarchy version does not suffer from the same problem, as recall is contingent on the recognition of schemas or patterns. This version, which accounts for the data on both game and random positions recall, offers then an explanation similar to that of the

chunking theory, though it does not offer clear mechanisms on how schemas and patterns are accessed. Note also that the two key mechanisms in the LT-WM theory—use of a retrieval structure and elaboration encoding through LTM schemas—do not play any role in this explanation. At worst, if encoding times are rapid with both mechanisms, as postulated by the theory, they would lead to a recall performance that is superior to human experts.

Number of Pieces

Chase and Simon (1973a) found that, presentation times being equal, their subjects (with the exception of the beginner) retained 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.

Referring to the chunking theory, 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 SEEK. 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 & Gobet, 1996, for an in-depth discussion of the properties of the chess game-tree). However, the fact that even masters cannot recall all pieces of an endgame position seems rather damaging for the square version of the LT-WM theory, which predicts a perfect recall, because few pieces, sharing many semantic relations (the positions are taken from master games) need to be encoded into the retrieval structure. The hierarchy version of the LT-WM theory can use Saariluoma's explanation, with the qualification that the encoding times into the retrieval structure and the LTM elaboration times have to be slow to avoid too high a recall percentage.

Recall of Games

The recall task has also been applied to sequences of moves. Chase and Simon (1973b) found a correlation between recall scores and skill, even for random move sequences. They also found that all players were slower to reproduce

random moves. According to them, strong players' superiority for random move 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. Finally, analysis of the 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,⁹ 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, but still better than the performance of novices, who were outperformed in the two other conditions.

The explanation of the chunking theory for actual games was mentioned earlier: the rather long presentation time of these experiments allows subjects to store information in LTM, such as creating new links in semantic memory or learning new chunks. In addition, the template theory also proposes that moves and sequences of moves may be chunked, with strong players having stored more and longer sequences of moves, and that the presence of templates makes storage easier for stronger players. Finally, the two theories can also use Saariluoma's (1991) following explanation. With random legal games, 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 after random moves. With random illegal games, however, chunks become harder and harder to find, and masters' performance drops. 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 drops 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.

SEEK explains performance with actual games by assuming that masters make use of prototypes, and also of compiled sequences of moves (Holding, 1985). It is more difficult for SEEK to account for masters' superiority in recalling random legal moves, because claiming that masters are more "familiar" with chess positions than non-masters only labels the phenomenon, but does not explain it. The type of knowledge proposed by SEEK—prototypes and generic knowledge—are not sufficient for explaining this result, as they are not available in positions arising both from legal and illegal random moves. Moreover, SEEK rejects the possibility of chunks, which, as we have seen, are crucial in explaining the difference between random legal and illegal games.

According to the two versions of the LT-WM theory, playing blindfold chess is made possible both by the retrieval structure, which allows players to rapidly update information about the position, and by the rapid elaboration of schemas in LTM. This explanation is consistent with masters' performance with actual and random legal games, but not with random illegal games. In this case, masters' low recall suggests that the retrieval structure is less powerful and the integration with LTM schemas slower than postulated by the theory. A solution is achieved by shifting the emphasis to recognition of LTM schemas, as is done in the hierarchical interpretation; however, this decreases the explanatory power of the retrieval structure and of LTM elaborations, which are central in Ericsson and Kintsch's (1995) account.

Modality of Representation

The chunking theory and the template theory propose that the main access to chess chunks is visuo-spatial (though other routes, such as verbal, are present as well), and that the mind's eye (internal representation), uses a visuo-spatial mode of representation. SEEK gives more importance to abstract and verbal types of representation. Finally, the LT-WM theory proposes a spatial mode of representation for the retrieval structure.

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. 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 referred to spatial representation, it was 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 were represented with a spatial structure. His results indicated that chess players obtained a better retention level when they listened to the description of a position¹⁰ 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. Finally, Charness (1974, study no 7) found that positions presented visually were better recalled (about 18%) than positions presented auditorily.

Using Baddeley's (1986) concurrent memory load paradigm, Robbins et al. (1995) studied the effect of interfering conditions during the presentation of chess positions. They found that a verbal task had only a minimal effect on performance, while a visuo-spatial task and a task aimed at suppressing the central executive caused a significant loss of performance (more than 2/3 in comparison with the control task). Interestingly, these authors observed similar effects on a chess problem solving 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 also been found by Saariluoma (1992). Combining the concurrent memory load paradigm with blindfold play, Saariluoma (1991) dictated sequences of moves from games at a rate of 2 s per piece moved and asked subjects to describe the location of all pieces after 15 and 25 moves. He found that concurrent 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.¹¹

Finally, masters' reports on the way they play blindfold chess have shed light on the type of representation used. Upon the analysis of the questionnaires he had sent to the best players of the time, Binet (1894) concluded that knowledge, more than visual images, played an essential role in blindfold chess, a role confirmed by subsequent research. In his description of (simultaneous) blindfold chess, former world champion Alekhine stresses the importance of logical rather than visual memory (Bushke, 1971). Fine (1965), another world class player, 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. I will take up the role of high-level representation in the section on conceptual knowledge.

In conclusion, there is very strong evidence that chessplayers use a visuo-spatial mode of representation, as proposed by both the chunking and the template theories. This visuo-spatial mode does not imply, pace 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 for a brief period of time, 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. The template theory specifically states 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.

According to SEEK, a large part of chessplayers' memory is encoded verbally. Empirical data (Charness, 1974; Robbins et al., 1995; Saariluoma, 1992) clearly refute this claim, and show that visuo-spatial encoding plays a much more important role. SEEK has little to say about the sorts of recoding present in Chase and Simon's (1973b) and Saariluoma's (1991) experiments. Finally, LT-WM's emphasis on a spatial mode of representation for the

retrieval structure is corroborated by the empirical data. In addition, the theory accounts for chess masters' ability to recode verbal input into a visuo-spatial representation through the storage capacity provided by the retrieval structure.

LTM Organization

This section presents empirical evidence for chunks, for conceptual organization of knowledge, and for the presence of a retrieval structure.

Direct Evidence for Chunks

The chunking and template theories make strong predictions on the structure of chunks. According to both theories, pairs of pieces that have numerous relations are more likely to be noticed together, and therefore chunked. Chase and Simon (1973a) analyzed the chess relations (attack, defense, proximity, same color and same type) between successively placed pieces in different tasks (a recall and a copy task) and in different types of positions (game and random), and found that the probabilities of these relations between successive pieces belonging to a chunk (less than 2 seconds' interval) are much greater than the probabilities between successive pieces not belonging to a chunk (an interval of more than 2 seconds). The basic analyses leading to chunk identification by Chase and Simon (1973a) have been recently replicated by Gobet and Simon (in press), who also provide new analyses supporting the chunking hypothesis.

Experiments using different techniques offer 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 & Adesman 1976).

The partitioning technique devised by Reitman (1976) for studying GO players' memory has also 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, 1996). 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). A partitioning procedure was also used by Freyhoff, Gruber and Ziegler (1992), with the addition that subjects were required 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, such chunks were 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, 1996), weak players asked questions about the location of single pieces, while experts asked questions about the past and future proceedings of the game, about plans and evaluations, and so on.

Taken together, these results support the concept of chunks and the estimate that it takes at least two seconds to access a new chunk and less than two seconds for retrieval within a chunk. However, they also indicate that strong players use higher-level types of descriptions. As discussed in the section on conceptual knowledge, the latter fact is accounted for by the template theory, but not by the chunking theory.

It is unclear how SEEK accounts for the results reviewed in this section, which offer strong support for the existence of chunks, which Holding (1985, 1992) explicitly denies. With respect to the square version of the LT-WM theory, additional assumptions (such as strategies during recall) are needed to account for the presence of chunks, since pieces may be retrieved from the

retrieval structure in an arbitrary order (Ericsson & Kintsch, 1995). The hierarchy version may account for this section results by making additional assumptions about the way patterns and schemas are organized in LTM. In principle, the same learning mechanisms provided by the chunking and the template theories could be incorporated into the LT-WM theory.

Number of Chunks in LTM

This section offers one of the rare instances where the predictions of different theories (SEEK vs. the chunking theory) have been directly tested experimentally. Commenting on Simon and Gilmartin's (1973) estimate that the number of chunks necessary to reach expertise was about 50,000, Holding (1985, 1992) proposed that this number could be decreased to about 2,500 if we are willing to assume that patterns are encoded independently of color and of location, that is, more abstractly. For example, a pattern shifted horizontally and/or vertically by several squares would be encoded by the same chunk in LTM because the functional relations among the pieces are maintained.

Gobet and Simon (1996c) tested Holding's claim by using positions that had been modified according to various mirror-image reflections (e.g., White and Black, or left and right are swapped). Their hypothesis, based on the chunking and template theories, 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. By contrast, a generic encoding, as proposed in SEEK, predicts no difference between the conditions. Gobet and Simon found that recall was slightly, but statistically significantly, impaired by such distortions. 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, and 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 (1996c) report simulations with a simplified chunking model that showed the same effects as human subjects in the mirror-image modification experiments. SEEK could account for these results by pointing out that LTM schemas or prototypes are harder to

access with the modified positions. (However, SEEK 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.) It is unclear how the square version of LT-WM accounts for the results reported in this section. Every “square” in the retrieval structure has the same encoding power, hence the LT-WM prediction is that modified positions should be recalled as well as 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. As for the hierarchical version of the LT-WM theory, it may account for the results with the additional assumptions that location is encoded in chess patterns, and that the time to encode patterns in the higher levels of the hierarchical retrieval structure and pieces on squares is not fast (else, the same difficulty as with the square version would arise).

Direct evidence for conceptual knowledge

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). The template theory specifies conceptual knowledge in detail, with templates acting as conceptual prototypes. SEEK clearly emphasizes the role of conceptual representation, by its assumption that chess players’ knowledge is stored at a higher level than the chunks proposed by the chunking theory. Finally, the LT-WM 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 in detail.

All four theories, therefore, agree about the role of conceptual knowledge, so the data presented in this section are not expected to discriminate strongly between them, as was the case with the data about random positions, where it is not possible to use conceptual knowledge. It is, however, important to review evidence related to this topic, for two reasons. First, these data are often incorrectly used as negative evidence against the chunking theory. Second, they

illustrate the strong differences that exist in the level of precision with which these theories are specified.

Several authors have shown that the presence of supplementary information on the position, even of an abstract kind, enhanced subjects' performance. Goldin (1978) 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.

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. At all skill levels, 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. Manipulating the levels of processing yields the same types of effect with recognition tasks (Goldin, 1978). Note, however, that recognition performance is high even with superficial tasks (more than 70% for class A players).

The importance of high-level representation has also been established experimentally by the analysis of protocols from problem solving (De Groot, 1946/1965) and recall tasks (De Groot, 1946/1965, Gobet, 1993a), as well as in a classification task (Freyhoff, Gruber and Ziegler, 1992). In particular, Cooke et al. (1993) showed that players took better advantage of a high-level description of a position when the description was given before rather than after the presentation of the position itself. Finally, there is strong evidence for a hierarchical representation of chess positions in memory (De Groot & Gobet, 1996; Freyhoff et al., 1992; Jongman, 1968).

As mentioned earlier, the experiments on semantic orientation have often been cited as negative evidence against the chunking theory (e.g., Cooke et al., 1993; Holding, 1985), though it is not clear why this 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 & Gilmarin, 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.

It is true, however, that high-level representations are not mentioned explicitly in the chunking theory, which focuses on low-level representations. The template theory removes this weakness by offering a mechanism on how chunks evolve into more complex and higher-level structures. 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 then have time either to encode smaller chunks or individual pieces in STM or to fill in information into the template slots.

Clearly, the experiments related to level of processing (Goldin, 1978; Lane & Robertson, 1979) support SEEK, which makes use of the prototype and level-of-processing accounts of chess memory. SEEK also offers an explanation, based on the idea of prototypes, for the high-level representations used by chess masters. However, it does not give details on how these prototypes are created. Finally, both versions of the LT-WM theory specify that the presence of LTM schemas explains the facilitating role of conceptual information or processing and accounts for experts' use of high-level representations. As with SEEK, however, there is no explanation of how these schemas are developed.

Direct Evidence for Retrieval Structures

The strongest evidence for the kind of retrieval structure advocated by the LT-WM theory is offered by Ericsson and Oliver (1984), cited by Ericsson and Staszewski (1989), who were interested in the speed with which chess experts can access information in the “internal chess board.” They asked their single

subject, an Expert, to memorize a 40-move game. 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 subject took only two seconds to make a move in the blindfold condition. 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 in 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. 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 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 s), 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. (SEEK could offer a similar explanation by using the concept of prototypes instead of chunks or templates.)

Unfortunately, Ericsson and Oliver's subject was not tested with random positions, which would have enabled us 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.)

Learning

The empirical data on chess learning may be classified into two different categories: short-range learning (in the order of tens of seconds) 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. As mentioned above, the key parameter here is that it takes about 8 s to create a chunk, and about 1 s to add information to an existing chunk (Simon, 1976). SEEK proposes that learning consists of creating prototypes and acquiring general principles but does not offer either precise mechanisms or quantitative predictions. Finally, the LT-WM theory implies that learning consists of creating the retrieval structure, of speeding up encoding and retrieval mechanisms, and of augmenting schematic LTM. No time parameters are offered by the theory, hence it is not possible to make quantitative predictions.

Short-Range Learning

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 overlapping with others) is high in the later stages. Thus, the quantity of information intake diminishes as the presentation time increases.

With game positions, Charness (1981b), using presentation times ranging from 1 to 4 s, and Saariluoma (1984), using times from 1 s to 12 s, provided results compatible with this hypothesis. The most complete set of data was supplied by Gobet and Simon (1995), whose players ranged 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 fits the data well ($r^2 > .90$).¹² Both parameters of this function (B and c) varied as a function of skill: compared with weaker players, stronger players memorized more with a presentation time of one second and took 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.

Early results about the effect of presentation time on random positions were difficult to interpret. On the one hand, Djakow et al. (1927) and Lories (1987) found a skill effect with a presentation of one minute (but see Gobet, 1993a, for methodological limitations of these studies). 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. Gobet and Simon (1995) offered more systematic data, varying the presentation from 1 to 60 seconds. As with game positions, an exponential growth function provided an excellent fit to the data. The surprising result was that the data with random positions showed the same pattern as those with game positions, with the qualification that the percentage of recall was lower with the former positions: players of different skills varied both in the amount of information they were able to memorize after an exposure of one second and in the rate with which they used 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 were able to replace correctly only about 17 out of 26 pieces (68%).

Saariluoma (1989) provided some interesting results both in connection with the influence of meaningfulness on recall and the role of presentation time. His methodology was similar to that used in the study of extraordinary memory for digits and restaurant orders (Chase & Ericsson, 1982; Ericsson & Polson, 1988). Positions were presented auditorily, one piece every 2 or 4 s (respectively 50 and 100 s for the entire position). An empty board was placed in front of the subjects. In accordance with Gobet and Simon's (1995) data on the role of presentation time, results indicated that strong players were better in the recall of game as well as random positions, and that performance increased, for all players and types of positions, with the increase in latency between the presentation of two successive pieces. Results also showed that recall superiority for strong players remained when subjects had to memorize 4 game positions, but that players of all categories performed poorly with 4 random positions. 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, 1996). As mentioned earlier, SEEK does not have much to say about the results on short-range learning.

Given that no time parameters are indicated, it is difficult to judge the fit of the LT-WM theory to the data with game position. The results with random positions and long presentation times seem, however, to be negative evidence against the square version of the 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, 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. As was the case with previous results, the hierarchical version could offer a reasonable account of the data, assuming that the encoding times into the retrieval structure and the LTM elaboration times are long enough, which seems however to contradict LT-WM emphasis on rapid encoding with experts.

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 fewer 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 (if anything, it was smaller on the re-test), 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, increase in selectivity) and not mainly through an increase in search mechanisms. Note that the chunk size (on average 2.7 pieces) was smaller than that 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, in press). The smaller inter-chunk latencies could speak in favor of this hypothesis. Although both SEEK and the LT-WM theory are not exposed in enough detail to offer an explanation of these results, two comments may be made. First, the size of DH's tree search and of his maximal depth of search run counter to SEEK's predictions that search is a key element of chess expertise. Second, the decrease in inter-chunk latencies could support the hypothesis of a retrieval structure.

Discussion

It is now time to summarize, for each theory, the positive and negative evidence (see Table 1). The reader is referred to the discussion at the end of each set of empirical data for details on the application of each theory.

 Insert Table 1 about here

The chunking theory does better than is often stated in the literature. The reason is that most criticisms were aimed at the computer model MAPP (Simon & Gilmarin, 1973), which implemented only a subset of the chunking theory. 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 recall of 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 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. Finally, the eye-movement simulations reported in De Groot and Gobet (1996) were obtained with essentially a chunking model.

SEEK is harder to judge, because many mechanisms are left largely unspecified. Intuitively, it captures the high-level descriptions reported by masters, allowing it to give some explanation for the interference studies and the roles of semantic orientation. Its weaknesses are with the recall of very briefly presented positions, with random positions, with the evidence for chunks and with the effect of board modification. In addition, SEEK's stress on verbal, in preference to visuo-spatial knowledge is not warranted by the data. Finally, SEEK does not say much about short-range learning. With long-range learning, it predicts larger changes in search parameters than observed by Charness (1989).

The square version of the LT-WM theory shares some of the difficulties shown by SEEK. Some data are not clearly handled, including interference studies, long-range learning, and evidence for chunks. Other data are directly at

variance with the predictions of the theory, such as recall of briefly presented positions and short-range learning. In particular, random positions are difficult to handle. 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 do not benefit from a retrieval structure with such positions. Other negative pieces of evidence are 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. Thus, while the square version makes relatively clear predictions, these are in many cases at variance with the empirical data, due to an excessively powerful retrieval structure.

The hierarchy version of the LT-WM theory does a better job at accounting for the data, although it is vague in many respects. In particular, two points came out quite clearly from the application of this version to the empirical data. First, the rapid recognition of schemas and patterns plays a more important explanatory role than the storage of new information, which is the central thrust of the theory. Second, it was necessary several times to make the assumption that encoding times into the retrieval structure and into LTM were relatively slow, to prevent the hierarchy version of the theory running into the same problems as the square version. But this seems to run counter to one of Ericsson and Kintsch’s (1995) main points, that encoding should be fast and reliable with experts.

In a sense, the template theory incorporates 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 actual 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. This concept 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, they account for the effects of semantic orientation and typicality.

Admittedly, the template theory and the LT-WM theory share many aspects: rapid encoding into LTM, importance of retrieval cues, small capacity of STM. The main difference between the two theories is illustrated by Figure 1. In the LT-WM treatment of most domains reviewed by Ericsson and Kintsch (1995), encoding through retrieval cues is not contingent upon the recognition of schemas in LTM; what I would call a generic retrieval structure is postulated. (Note that Ericsson and Kintsch's treatment of text comprehension does not presuppose the presence of a generic retrieval structure but proposes two sources for retrieval structures: the episodic text structure, which is rapidly built up during the comprehension of a text, and LTM schemas. It is however debatable whether the episodic text structure matches the criterion of stability proposed by Ericsson and Kintsch as defining retrieval structures; see Gobet, 1997, for a discussion.) 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, 1997). 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 generic retrieval structures develop within domains such as medical expertise or chess, or in other domains where there is no deliberate attempt to improve one's memory. The concept of generic 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 strategic control, and where the input is encoded serially. Chess, which offers a bi-dimensional structure where reliance on the order of encoding is not important, and which is a domain where memory of positions is not a primordial goal, does not fit this description, nor do many (most?) other domains of expertise.

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 perception, memory, and problem solving (see Gobet, 1997, for an application of the theory to problem solving). 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 accounts for a large amount of empirical data from the learning and memory literature and has recently been used to simulate the behavior of a mnemonist specialized in the digit-span task, one of the tasks which led to the development of the skilled memory theory (Chase & Ericsson, 1982).

Several general conclusions that extend beyond the realm of chess may be formulated. First, the chunking theory fared very well, better than is normally proposed in the literature. Second, perception plays a critical role in cognition. This was already the message of De Groot, Chase and Simon. Interestingly, research in Artificial Intelligence (e.g., Brooks, 1992) now echoes these scientists. Third, comparing data across the traditional barriers of perception, memory, and problem solving offers definite advantages, as was most eloquently formulated by Newell (1973), including a reduction in the number of degrees of freedom allotted to the theory. As an example, consider the CHREST model, the computer instantiation of the template theory. Parameters derived from memory, such as those directing the creation of chunks, were used in simulating eye movements. Conversely, constraints on eye movements, such as the size of parafoveal vision, were used to simulate the creation of chunks.

Fourth, the comparative method used in this paper clearly illustrates the weaknesses of verbal theories: vagueness, non-refutability, and ease of adding auxiliary assumptions, which may not be compatible with the core of the theory. For example, the auxiliary assumption that encoding times are slow, which I made repeatedly with the LT-WM theory to avoid its predicting too strong a recall performance, seems reasonable. However, it clashes with LT-WM emphasis on rapid encoding times. Noting the deficiencies of theories formulated verbally has been done frequently in the past, but had to be reiterated here, because many theories are still formulated only verbally in the research on expertise—chess is no exception. Of course, and fortunately, there are also quite a few attempts to frame theories in rigorous formalisms (e.g., the research carried out within the Soar and ACT-R frameworks). Fifth, the decision to prefer precise predictions within a specific domain to loose predictions across various domains has definite advantages. Not least of them is the fact that this approach recognizes the importance of the constraints imposed by the task domain (Ericsson & Kintsch, 1995; Newell & Simon, 1972). While it is important to search for general cognitive principles, such as the roles of chunking, retrieval structures, or high-level knowledge, one should not forget that each domain of expertise imposes constraints that critically shape behavior. These constraints may be lost when theories are compared loosely across several domains, which implies that the analysis of the match between theory and data is done at a general level, with the risk that too many "details" are lost.

The impact of chess research on cognitive science in general and on the study of expertise in particular 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. Whether it will be

as successful in other domains of expertise, or whether another theory would fare better, has to be established by rigorously testing it against empirical data along several dimensions, as has been done in this paper for chess.

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Figure captions

Figure 1. Illustration of the two different types of encodings according to the LTWM theory. The top of the figure shows a hierarchical organization of retrieval cues associated with units of encoded information. The bottom of the figure depicts knowledge based associations relating units of encoded information to each other along with patterns and schemas. (Adapted from Ericsson and Kinstch, 1995.)

Figure 2. Schematic representation of the processes carried out by MAPP. The upper part of the Figure depicts the learning phase, where chess patterns are fed to an EPAM-like discrimination net. The lower part illustrates MAPP processes during a recall task: (a) salient pieces in the stimulus position are detected; (b) salient pieces plus the pieces around them are fed to the discrimination net, which, when a chunk is recognized, outputs a symbol; (c) the chunk symbols are placed in STM; and (d) the position is reconstructed using the symbols in STM and the chunks they point to in LTM. (After Simon & Gilmartin, 1973.)

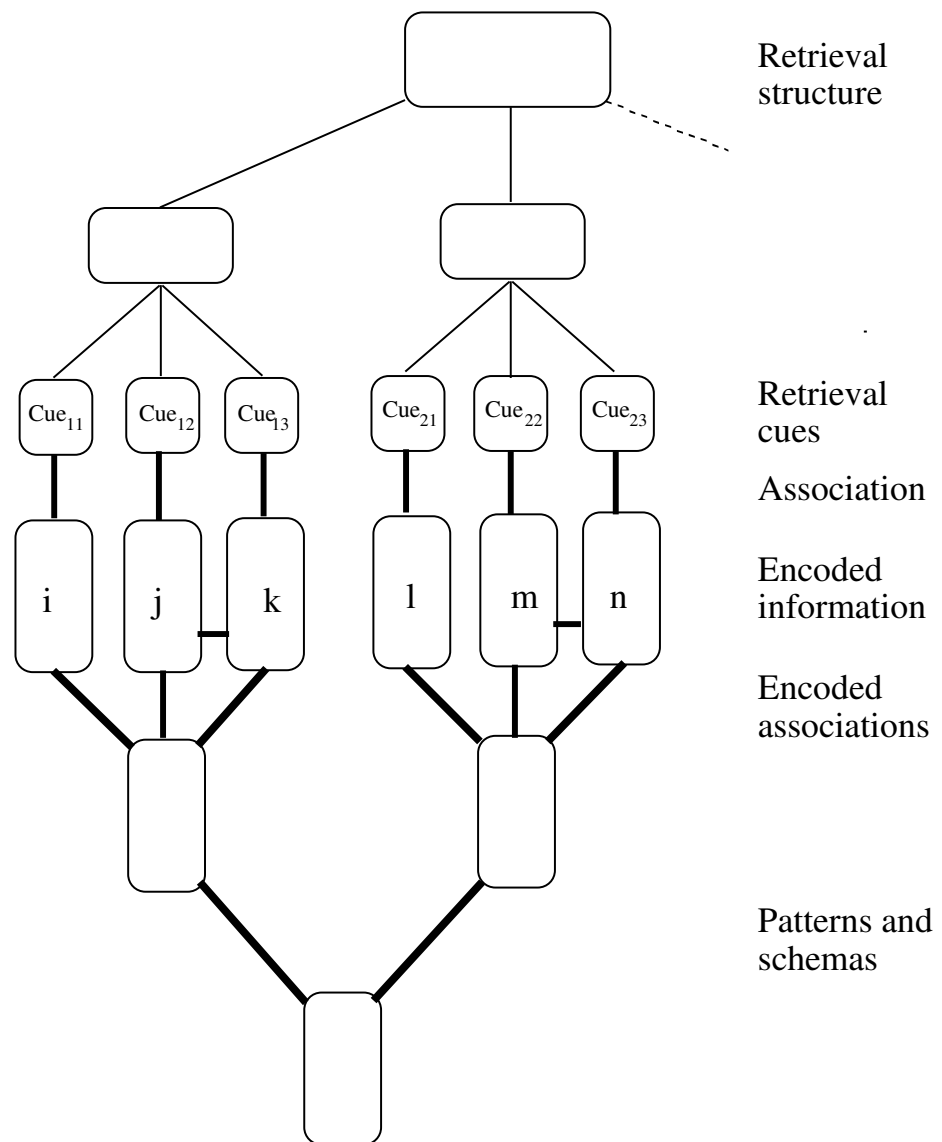


Figure 1

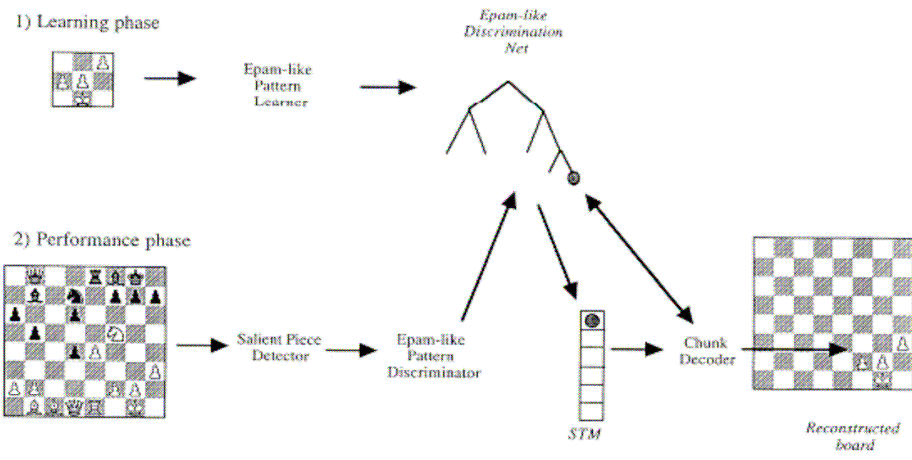


Table 1: Overview of the Fit of the Four Theories with Empirical Data

Empirical domain	Theory				
	Chunking theory	Template theory	SEEK	LTWM (square version)	LTWM (hex version)
<u>Early perception</u>					
Short presentation times	+	+	?/-	-	-
Eye movements	+	+	?	?	-
<u>STM recall and LTM encoding</u>					
Interference studies	-	+	?/+	?/+	-
Random positions	+	+	-	-	-
Number of pieces	+	+	+	-	-
Recall of games	+	+	?/-	-	-
<u>Modality of representation</u>					
Visual vs. verbal encoding	+	+	-	+	-
<u>LTM organization</u>					
Evidence for chunks	+	+	-	?	-
Number of chunks (distorted positions)	+	+	-	-	-
Evidence for conceptual knowledge	?	+	+	+	+
Evidence for retrieval structure	?/+	?/+	?/+	?/+	?/+
<u>Learning</u>					
Short-range	+	+	?	-	-
Long-range	+	+	?/-	?/+	-

Note: “+” indicates that most data are accounted for by the theory;

“-” indicates that some data refutes the predictions of the theory;

“?” indicates that the theory does not make clear predictions or that the data are preliminary.

Footnotes

¹ The ELO rating assumes that competitive chess players are distributed with a mean of 1500 and a standard deviation of 200. In this paper, I will use the following denominations: grandmaster (>2500), international master (2400-2500), masters (2200-2400), expert (2000-2200), class A players (1800-2000), class B players (1600-1800), and so on...

² As noted by a reviewer, patterns and schemas play a key role in the LT-WM theory. It is therefore regrettable that Ericsson and Kintsch (1995) do not define these terms. Their usage seems compatible with the following definitions: a pattern is a configuration of parts into a coherent structure; a schema is a memory structure that is made both of fixed patterns and of slots where variable patterns may be stored.

³ De Groot's grandmaster was Max Euwe, world champion from 1935 to 1937.

⁴ The template theory emphasizes a limited-size visual STM, containing about three chunks (cf. Zhang & Simon, 1985), and somewhat downplays the role of verbal STM. The reason is that labels used by chess players to characterize types of positions can be quite long (e.g., “Minority attack in the Queen’s Gambit declined”), and may at best be seen as redundant encoding. This does not mean, however, that chessplayers do not use verbal memory—they do. The complete theory should incorporate a verbal STM as well, such as that proposed in EPAM IV by Richman et al. (1995), where the idea of chunk is combined by the concept of articulatory loop proposed by Baddeley (1986).

⁵ This version did not incorporate templates. De Groot and Gobet (1996) suggest that the same results obtain with the presence of templates.

⁶ As a matter of fact, De Groot (1946/1965) himself recommended to his subjects a waiting delay of about 30 s before reconstructing the position. This interval was supposed to allow the subject to “organize whatever he could remember.” Chase and Simon (1973b) also tested the effect of a waiting task with one of

their subjects and did not find any performance loss in recall in comparison with immediate recall.

⁷ While retrieval from LTM seems obvious when subjects were trying to remember a position for several minutes, other shorter latencies to retrieve the position do not forcibly speak for an exclusive access to LTM: the pointer may still be in STM, but time is needed to “unpack” it and to access the contents of chunks and templates.

⁸ Vicente and Wang (in press) note that, in most experiments, random positions are created by randomizing the location of pieces from game positions, and that no one has used positions where both the location on square and the piece distributions are randomized.

⁹ In blindfold chess, a player carries out one (or several) game(s) without seeing the board and the pieces (moves are indicated using standard chess notation).

¹⁰ Charness (1974) used 4x4 matrices that contained 8 pieces.

¹¹ In this task, concurrent is defined as occurring after the dictation of each individual move. Posterior interference is defined as occurring after the dictation of a sequence of moves.

¹² $P = 100 - Be^{c(t-1)}$, where P is the percentage correct, 100-B is the percentage memorized with one second, c is the constant of proportionality, and t is the presentation time.