

Shortcomings of generic retrieval structures with slots of the type that Gobet (1993) proposed and modelled

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In this issue Gobet (2000) reports on his continued efforts to compare computational models of expert's superior memory of chess positions within the template theory (TT) framework (Gobet, 1997, 1998; Gobet & Simon, 1996, 1998), to Ericsson and Kintsch's (1995) theoretical framework for long-term working memory (LTWM). Comparisons of theoretical frameworks can be very valuable and provide the broader scientific community with a clear picture of the strengths and weaknesses of the competing theoretical proposals when the theories being compared share many basic assumptions and mechanisms. Unfortunately, it is difficult to compare LTWM's general theoretical framework for how experts can acquire expanded working memory to support their superior performance in many domains of expertise to TT's explicit computational mechanisms for simulating a specific type of performance, such as chess players' memory for presented regular and random chess positions. As these two theoretical frameworks have been independently developed to account for different empirical phenomena and also differ in the specificity of their proposed concepts and mechanisms, it becomes very difficult to compare them without making questionable interpretations and extrapolations.

Anyone who is not familiar with the extensive literature on retrieval structures, templates, and LTWM, might reasonably (though incorrectly) assume that all papers use the term retrieval structures to refer to mechanisms with similar basic characteristics. This assumption may have been reinforced by the fact that the same issue of *Psychological Review* contained two different papers, Ericsson and Kintsch (1995) and Richman, Staszewski, and Simon (1995). Both papers used Chase and Ericsson's (1982) skilled memory theory and its proposed storage in long-term memory (LTM) through retrieval structures as their point of departure. Given that the two papers involved authors with long-standing collaborative relationships (Ericsson & Simon, 1980, 1984, 1993; Ericsson & Staszewski, 1989), it would make

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sense to assume that the papers were tightly coordinated. One proposed a computational model in EPAM of a digit-span expert (Richman *et al.*, 1995), while the other (Ericsson & Kintsch, 1995) proposed a broader generalization to skilled and expert performance drawing on the same or, at least, consistent mechanisms. In reality, the two theories were developed independently during the early 1990s. The fact that they appeared in the same issue was a complete coincidence. The reason that neither paper cites the other reflects the fact that both research groups were apparently unaware of each other's respective papers and proposals.

In our commentary we will argue that Gobet's criticisms of LTWM failed to recognize the basic differences between the retrieval structures discussed in Ericsson and Kintsch's (1995) LTWM and the retrieval structures explicated by Richman *et al.* (1995). As part of our rebuttal we first need to provide an accurate description of the development of LTWM. Consequently, our commentary has three parts. First we will describe the independent development of computational models of superior memory performance of chess experts within the Elementary Perceiver and Memorizer (EPAM) framework and our proposal for how experts can acquire expanded working memory via LTWM to support memory demands while performing tasks representative of their domain. We will show how these two research approaches differ in regard to theoretical issues analysed and empirical phenomena reviewed, as well as their use of simulations within cognitive architectures. Then, we will describe Gobet's (1998, 2000) efforts to further specify the mechanisms of LTWM so they could be interpreted as computational mechanisms within the tightly constrained EPAM architecture. We will argue that Gobet mistakenly inferred that Ericsson and Kintsch's (1995) extension of Chase and Ericsson's (1982) retrieval structures would, if sufficiently further specified, match the explicit computational mechanism proposed by Richman *et al.* (1995) in their EPAM model for the digit-span expert (DD).

Richman *et al.* (1995) proposed a retrieval structure mechanism consisting of a list of slots where individual digits could be directly stored at rapid rates, thus meeting Gobet's (2000) definition of a generic retrieval structure. Gobet was intimately familiar with these types of retrieval structures as he is credited (Richman *et al.*, 1995) with being the first to implement them in his computer simulation of chess experts' superior memory (Gobet, 1993). However, generic retrieval structures were later rejected as a valid explanation of chess experts' superior memory by Gobet and Simon (1996), who proposed a modified version referred to as templates. We will show that both generic retrieval structures and templates rely on slots for storing for individual digits or individual chess pieces. The idea of slots, where individual elements can be stored independently of meaningful associations to other elements at fixed time durations, was explicitly rejected both by Chase and Ericsson's (1981, 1982) skilled memory theory¹ and even more comprehensively by Ericsson and Kintsch's (1995) LTWM. Consequently, like Gobet, we have always been critical of

¹ The lack of transfer of information from Chase and Ericsson (1981, 1982) to Richman *et al.* (1995) might seem improbable to outsiders. However, Ericsson moved from Carnegie-Mellon University to the University of Colorado in 1980, and Bill Chase passed away in 1983. This forced Staszewski to take over the testing of DD, who had at that time reached a digit-span of over 60 digits. Given that Staszewski was primarily committed to independently completing his doctoral dissertation at Cornell University, he and Ericsson never pursued collaborative research.

generic retrieval structures as a model of chess experts' memory for chess configurations. Thus, we agree with Gobet's (1998, 2000) extensive criticisms of this mechanism, but not with his claim that LTWM proposes generic retrieval structures as part of its mechanisms.

In the concluding section, we will discuss the problems that arise in developing and testing theories of expert performance due to the extreme complexity of the acquired mechanisms. We will show that LTWM starts by capturing the naturally occurring phenomenon in the laboratory and then proceeds by analysis and designed experiments. Gobet and Simon's (1996, 1998) work on templates starts with basic capacities and elementary processes and gradually introduces more complex mechanisms as they are required to explain data from groups of chess experts and novices. We will also suggest that the two approaches may well soon meet to allow a coordinated effort to understand the extraordinary complexity of expert chess performance.

Brief historical background for the two different theoretical approaches

By the end of the 1980s, it was generally recognized that memory performance on psychometric tests of short-term memory (STM) could be improved dramatically through practice by acquiring skill to store information in LTM. Several college students (SF, DD, RE) improved their digit-span by 200–1300 % in 50–400 hours of practice (Chase & Ericsson, 1981, 1982; Ericsson, 1985; Ericsson, Chase, & Faloon, 1980) and analyses of mnemonists and memory experts showed evidence for similar acquired mechanisms (Ericsson, 1988; Ericsson & Polson, 1988a, 1988b; Wilding & Valentine, 1997). The associated improvements in memory performance reflected acquired skills that permitted rapid LTM storage and efficient information retrieval, thus increasing the capacity of working memory without changing STM's basic transient storage capacity. There were also several preliminary proposals (Chase & Ericsson, 1982; Ericsson & Staszewski, 1989) that related the mechanisms involved in exceptional memory for digits and dinner orders to the superior memory of experts, such as chess players and experts in mental multiplication. These proposals also contained preliminary accounts of the pioneering research by Charness (1976) and Frey and Adelman (1976), showing that chess experts are able to rapidly store information in LTM even after brief exposures of chess positions. This new research directly questioned the assumptions of Chase and Simon's (1973) famous theory based on storage solely in STM.

These highly reproducible findings for acquired memory skill served as points of departure for both the theoretical development of models of expert memory within EPAM and the development of LTWM to account for working memory during expert performance. Let us first examine the theoretical development of models within the EPAM framework and their new mechanisms involving 'slotted schemas' to explain rapid storage in LTM, before describing the different theoretical issues addressed by Ericsson and Kintsch's (1995) LTWM. Given that we believe that Gobet (1998, 2000) has misinterpreted our ideas, we will make an extended effort to support all our important claims with extensive direct quotes by Gobet and his colleagues to minimize the risks that we commit the same type of error.

The addition of new mechanisms to the EPAM theory that would permit rapid storage in LTM by skilled performers

Many theories in cognitive psychology and cognitive science are expressed as computer models, where cognitive processes for successfully performing tasks are specified within an architecture of constraints on human information processing. One of the first architectures, Elementary Perceiver and Memorizer (EPAM), was proposed by Feigenbaum and Simon (1962; Simon & Feigenbaum, 1964). One of EPAM's basic assumptions was that storage of any new piece of information, such as a chunk, in LTM corresponded to a unitary process that generalized to all types of materials and required the exact same amount of time for successful storage in LTM. Based on estimated rates of memorization in laboratory studies, the required time for storage in LTM was estimated to be around 8 seconds, or some specific number between 5 and 10 seconds (Simon, 1974). The rapid storage in LTM demonstrated by Charness (1976) and Frey and Adelman (1976) would seem to violate EPAM's basic assumption that LTM storage was slow. This fact was acknowledged early by Simon (1976, 1979), who speculated that it may be necessary to differentiate different rates for different types of storage in LTM and that 'storage of new information in semantic memory may be quite rapid' (p. 79) for experts who have acquired sufficient knowledge and skilled mechanisms.

In 1991, Richman, Simon and Gobet proposed (paper presentation cited in Gobet and Simon, 1996, p. 30) that retrieval structures such as those proposed by Chase and Ericsson might provide a faster storage process, whereby the required duration for storage in LTM would still be constant, but much shorter than 8 seconds. A couple of years later Gobet (1993, p. 463) published a description of an explicit computational mechanism for simulating expert chess memory using 'the implementation of the concept of *retrieval structure* (Chase & Ericsson, 1982), which is a long-term memory (LTM) template into which information can be encoded rapidly'. Gobet's proposal for this mechanism is clearly described in de Groot and Gobet (1996, p. 118): 'The main idea with this model was that chess players build up a structure which is similar to SF's or DD's, except that it is a bi-dimensional structure, isomorphic to the 64 squares of a chess board. "Squares" of this structure would act as slots to store men [chess pieces] or chunks.'

Although Gobet's (1993) simulation model showed 'a satisfactory fit with the data' (p. 468) overall, his model recalled random chess positions far better than his human chess experts. Gobet (1993, p. 468) expressed confidence in the validity of his retrieval structure mechanism, and even speculated that the chess players' discrepant recall of random positions might be due to 'emotive factors (human subjects show very strong negative affects when confronted to random positions)'. More significantly, he restricted 'the retrieval structure to a few slots, say one for the center one for the King's side, and so on' (p. 468) which improved the fit between his model and human chess experts.

A few years later when Richman *et al.* (1995) published their EPAM IV simulation of the digit-span expert, DD, they explicitly acknowledged that Gobet (1993) had developed the first computer implementation of the core innovative mechanism—the retrieval structure. 'The principal and essential novelty in EPAM IV is the presence

of the retrieval structure with its rapidly fillable slots and the association of these slots with learned chunks in semantic memory' (p. 311). 'Only specific types of information can be stored in these slots. A schema with slots for numbers cannot store letters, and vice versa; a schema with slots for chess pieces cannot store playing cards' (p. 314).

Richman *et al.*'s (1995) computer simulation model relied on specific retrieval structures where 'Each slot on a node can hold only one of small set of values of particular attribute. For example, most of the slots on DD's retrieval structure nodes can hold only a single digit each' (p. 315). The simulation model for DD assumes that it takes '200 ms to attach the digit to the retrieval structure node' (p. 320). Storage of each individual digit within the retrieval structure in LTM can be done independently of any associations with other digits in the list and therefore meets the definition of a generic retrieval structure (Gobet, 1998, 2000). The simulation model of DD assumes some forgetting of digits stored solely in the generic retrieval structure and the probability of subsequent recall of any digit at the end of presentation of a long digit list is around 75% (p. 319). Given that digit-span requires perfect (100%) recall of the list of digits, 'the retrieval structures alone cannot explain DD's (or EPAM's) ability to retain long lists' (p. 319) and storage in the retrieval structure needs to be supplemented by encoding of 'semantic categories (e.g., running times, ages) for sublists of three or four digits each' (p. 310) and 'numerical pattern codes (i.e., symmetries like 13-31, 27-27) used to recognize higher order patterns explicitly (Staszewski, 1990, 1993)' (p. 310). However, the semantic encodings and numerical pattern codes were judged to 'offer no novelty', (p. 310) because they could be handled by existing mechanisms in EPAM for storage in LTM.

Richman *et al.*'s (1995) simulation model was tested against memory experiments designed by Staszewski (1988) to study the digit-span expert (DD) when DD had already reached a very high level of proficiency, with a digit-span around 90–100 digits.² The ability of the model to reproduce DD's memory performance successfully in those experiments shows that the hypothesized mechanism involving a generic retrieval structure is sufficient to reproduce several aspects of DD's memory performance. However, it does not prove that the generic retrieval structures are the only mechanism that could do so, nor even that these mechanisms are valid accounts of DD's performance—especially if the model had to reproduce results from several other experiments. It is important to note that none of the more than a dozen experiments conducted with DD by Chase and Ericsson (1981, 1982) while he increased his digit-span from around 7 digits to over 60 digits (the first 300 practice sessions) were used to evaluate the assumptions of Richman *et al.*'s (1995) simulation model of DD.

The principal theoretical issue for us (and, as it turns out, for Gobet, 1998, 2000)

² Until his death in 1983 Chase conducted virtually all the training and the experiments with DD. Staszewski continued the testing of DD and he later independently designed and analysed a series of studies for his doctoral dissertation completed at the Department of Psychology, Cornell University. In his subsequent publications Staszewski limited his discussion to those data that he had collected independently by himself. In his most recent publication as a sole author, Staszewski (1993) claimed that DD *always* encoded the digits into groups of '3 or 4 digits as an organized, meaningful chunk' (p. 972) which would seem inconsistent with Richman *et al.*'s (1995) simulation model which allowed encoding of a digit at a time into the slots of the retrieval structure without prior semantic encoding.

is the validity of the hypothesized generic retrieval structure mechanism which implies that experts such as DD would possess a remarkable capacity for storing elements (individuals digits) independently within the retrieval structure at impressively fast rates. In a cognitive architecture such as EPAM the availability of a mechanism in one area of expertise would imply its availability in other domains of expertise. Consequently, it must be possible for experts in other domains, such as chess, to acquire retrieval structures for similarly rapid storage of relevant information in LTM. For example, how could a chess expert remember a chess position using generic retrieval structures? In this current paper Gobet (2000, p. 556) describes the argument well: 'A first interpretation is that pieces are encoded into the squares of the retrieval structure. This interpretation runs into several problems, however, ... In chess, where masters can recall almost perfectly a position containing 25 pieces with a presentation time of 5 seconds, we have to assume that individual units of information (the chess pieces) are encoded into the retrieval structure very fast, in the order of 200 milliseconds (5 seconds divided by 25).' This highly implausible mechanism would predict the same recall performance for random and regular chess boards, instead of the large recall advantage for regular boards that is actually observed.

Richman *et al.* (1995) were aware of Gobet's concerns about this problematic generalization of generic retrieval structures and proposed a superordinate concept of 'A slotted schema' (p. 308) that included generic retrieval structures and other types of memory structures 'having at least one variable among its attribute values' (p. 308). Richman *et al.* argued that any time individuals, such as DD, engage in deliberate practice to improve their memory performance for some material, such as random digits, these trained individuals acquire generic retrieval structures—slotted schemas that 'contain only slots' (p. 306). In contrast, the superior memory of chess players is acquired incidentally 'in the course of study and play' (p. 306) and invokes different types of mechanisms that are called templates. 'For the chess expert, it appears that the schemas are based on the pattern of a chess board on which squares have slots with which pieces, pattern of pieces, and other information can be associated and on the typical patterns of pieces in chess openings that are known to master players (Gobet, 1993)' (Richman *et al.*, 1995, p. 306).

In a subsequent paper Gobet and Simon (1996, p. 29) proposed a more detailed description: 'The templates specify the locations of perhaps a dozen pieces in the position (thus specifying a class of positions), but also contain variables (slots) in which additional information can be placed, thus fixing the positions of additional pieces.' Gobet and Simon's (1996) templates introduce a new level of complexity and richness compared to the earlier mechanisms involving chunks and Richman *et al.*'s (1995) generic retrieval structure.

A very simple mechanism can model the process of acquiring new chunks by merely exposing chess positions to the model and allowing it to copy some of the patterns of the position and store them in LTM. Similarly, generic retrieval structures are hypothetically acquired by adding on individual slots or sequences of slots to the LTM structure (Richman *et al.*, 1995). A far more complex process of acquisition is proposed for templates by Gobet and Simon (1996, p. 29): 'The templates are implicitly acquired by chess players in the course of their study of

games, both those they play and those they examine in the chess literature.' Consequently, a full-fledged simulation model of the acquisition of templates would thus require a simulation model of the cognitive processes involved in both playing chess games as well as studying and examining games from the chess literature. However, Gobet (1997, pp. 298-299, emphasis added) makes it very clear that a model for playing chess, even evaluating a chess position, was outside the scope of his current simulation models: 'Full implementation of TT [Template Theory] as a chess-playing computer program would be a major task... This model does not constitute a complete implementation of the theory (it *does not search or evaluate chess positions*), but is detailed enough to offer a good test of some aspects of TT. It is sobering to notice that even this partial implementation of the theory is quite complex and requires many parameters. This is the price of avoiding the vagueness of verbal theorizing.' Hence, TT proposes templates to explain all the aspects of memory performance for random and regular chess positions yet acknowledges that to explain fully the acquisition of the templates it will be necessary to develop a far more complex theory that explains the processes mediating how chess experts study and evaluate chess positions and how they can play games at an expert level.

In sum, TT offers by far the most complete analysis and explicit model of recall of chess-related stimuli as a function of chess skill, but its scope is limited to memory and reproduction of chess positions.

Skilled and expert performance and its demand for expanded working memory (LTWM)

In an independent strand of research activity during the 1980s, Ericsson and Smith (1991) started to examine the theoretical basis for a relation between expertise and experts' superior memory. In their influential theory of expertise Chase and Simon (1973) proposed that it was necessary for experts to acquire a large body of chess patterns to attain an expert level of chess playing. The acquisition of chess patterns and chunks was relatively slow, which explained why many years of chess playing were necessary to reach expert levels. The superior memory of chess experts over novices for regular chess positions but not randomly rearranged chess positions was explained by the experts' ability to rely on their acquired chess patterns to encode familiar configurations of chess pieces. During the 1970s and 1980s, many investigators replicated the expertise advantage in recall for representative stimuli for many domains of expertise and endorsed Simon and Chase's (1973) 10-year rule which stated that about 10 years or more of intense domain experience was necessary to reach an international level of performance, as well as distinctly superior memory. However, in the 1980s, a couple of findings emerged that seemed to question the strength of the link between superior memory performance and expert performance.

First, Ericsson and Chase (1982) had already shown that *within 50 hours* of practice their digit-span experts were able to reach a level of memory performance for digit sequences that exceeded that of experts in mental multiplication and professional memory experts with 20-40 years of experience. Similarly, Ericsson and Harris (1990; Ericsson & Oliver, 1989) demonstrated that a student who had never played chess was able to recall chess positions after *a mere 50 hours* of memory practice at a level comparable to that of chess experts with thousands of hours of chess playing

(Charness, Krampe, & Mayr, 1996; Simon & Chase, 1973). A detailed analysis by Ericsson and Harris that revealed the trained participant's superior recall was mediated by primarily superficial patterns of similar chess pieces, in contrast to chess experts who focused on the relations between chess pieces that were critical to selecting moves for the chess position. Similarly, mental-multiplication experts encode numbers in terms of their numeric properties, such as decomposition in prime numbers ($893 = 19 * 47$), to facilitate speeded calculation, so they would not benefit from the more efficient mnemonic encodings of numbers, such as those used by SF and DD.

These and numerous other findings (Chase & Ericsson, 1982; Ericsson, 1985) demonstrate that memory for many types of materials improves gradually as a function of practice and leads to superior and occasionally exceptional level of memory within 50–100 hours. If expert memory performance can be attained in a fraction of the number of years necessary to acquire expert chess-playing skill, then this raises doubts about the necessity of a tight connection between expert performance and experts' superior memory for representative stimuli.

Toward the study of representative performance that captures the essence of expertise. The real challenge in acquiring expertise in a domain appears to be acquiring encoding skills that mediate extraction and storage of information relevant to representative performance in the domain of expertise. In their review of research on expertise, Ericsson and Smith (1991) found that the pioneering researcher in chess, de Groot (1946/1978), had demonstrated that the best laboratory task to capture the essence of expert performance in chess consists of presenting unfamiliar chess positions and asking players to select the best move. Subsequent reviews (Ericsson & Lehmann, 1996; Ericsson, Patel, & Kintsch, 2000) have confirmed that performance on the move selection task is far more predictive of performance at chess tournaments (the ultimate criterion for chess skill) than is memory performance for briefly presented chess positions. This finding must imply that the move selection task is mediated by the processes and representation used during actual chess playing to a higher degree than the memory tests for chess positions.

It is worth noting that if experts are tested on the same memory task repeatedly to assess their complex mediating processes (cf. Ericsson & Polson, 1988a, 1998b) they can markedly increase their memory performance. Ericsson *et al.* (2000) showed that chess players improve their memory for briefly presented chess positions as a function of experience with the specific memory tests. In other cases memory performance has been shown to increase dramatically (Gobet & Simon, 1996) when a chess master with extended training changed his cognitive processes by adopting mnemonic encodings that were so effective for non-experts in their dramatic improvements of memory.

If, however, the laboratory task captures the natural constraints of the representative performance in a domain, a few or even a dozen hours of additional experience during testing are unlikely to change a performance attained after thousands of hours of deliberate efforts to improve it (Ericsson & Smith, 1991). In an attempt to follow the implications of this argument, we (Ericsson & Kintsch, 1995) excluded results from studies of expert memory, unless the particular expertise

was defined by the superior memory performance, such as the waiter JC's ability to remember dinner orders. Hence, we intentionally avoided any discussion of results from studies of experts' memory for random and regular chess boards. In a subsequent paper Ericsson *et al.* (2000) proposed how LTWM acquired to support representative performance could explain experts' superior performance on laboratory tests of memory for domain-specific stimuli.

In our proposal for LTWM, we claimed that skilled and expert performers can expand functional working memory during the performance of representative tasks in their domain of expertise by acquiring skills to store information efficiently in LTM. We first showed that experts' working memory relies on LTM in many domains and that experimentally induced interference with information in STM does not totally disrupt performance because the experts can often resume their activity after regaining access to relevant information in LTM. How is the information related to experts' working memory kept distinct from the vast amount of other information in LTM? How can information once stored in LTM be reliably and efficiently accessed whenever it is later needed during the task-related activity? Our central idea was that experts with their deep knowledge of the task can anticipate future retrieval demands for information. By acquiring encoding skills, the experts can pre-process information at the time of encoding and anticipate its future use and thus associate it with appropriate features and semantic cues. These cues will then allow efficient retrieval of relevant information when needed later in processing.

We proposed two types of interacting associative mechanisms that would allow experts to maintain selective access to relevant information from the current task and distinguish that information from information stored in LTWM during earlier performance of similar tasks. One aspect of acquiring expert performance requires that experts extract a system of cues that they repeatedly use to index specific semantic categories of information. They generate associations to these types of cues to allow retrieval of the most recently encoded information through reinstatement of those retrieval cues, even when this type of information is frequently updated and changed during the processing. To counteract problems with proactive interference these retrieval cues need to be embedded in 'generated structures in LTM', where presented information is interrelated to other pieces of presented or generated information. It is important to note that we were not describing two distinct types of independent mechanisms but rather different types of associations within integrated memory structures in LTM. Our ideas have been elaborated in more recent publications (Ericsson & Delaney, 1998, 1999; Ericsson *et al.*, 2000; Kintsch, 1998; Kintsch, Patel, & Ericsson, 1999).

LTWM in chess. We stated clearly (Ericsson & Kintsch, 1995, p. 233) that 'The best laboratory task for capturing chess skill involves the selection of the next move for an unfamiliar chess position (de Groot, 1946/1978; Ericsson & Smith, 1991),' In the brief section on chess (less than 10% of the entire paper), we reviewed evidence for storage in LTM during the move-selection task and showed that chess players have substantial incidental memory during post-session recall and no reliable memory deficit from interpolated interference with STM. We reviewed evidence suggesting that chess players acquire LTWM to facilitate planning and reasoning about move

selection for chess positions. For example, ‘depth of planning during the selection of a move increases with chess skill up to the level of an advanced chess expert. Increases in chess skill beyond this level are associated with a more sophisticated focus on evaluation and abstract planning’ (p. 237). Highly skilled and even world class chess players frequently discover better moves through planning during the several minutes of deliberation before they announce their move for a chess position (de Groot, 1946/1978; Saariluoma, 1990).

What are the characteristics of LTWM that would allow chess players access to information stored in LTM about the chess position to allow planning? We proposed that ‘A chess position is represented as an integrated hierarchical structure relating the different pieces to each other, and all pieces are associated with their corresponding locations’ (p. 237). We reported that chess players are able to respond rapidly to unexpected requests for information about chess positions in memory, such as ‘What piece is in location X for Board A?’ and ‘How many opposing pieces attack location Y?’ We also reported evidence that chess players become increasingly better at playing chess games mentally as the corresponding moves are called out as a function of chess skill. Perhaps the best evidence for a highly refined mental representation based solely on storage in LTM (LTWM) is shown by the ability of chess masters to play at a high level under blindfold conditions—without a perceptually available chess board. The world-chess player Anatoly Karpov (1995, p. 912) even claims that ‘sometimes you have games of such very high quality that you could not tell it is blindfold chess’.

How are these refined representations and LTWM acquired? Drawing on Ericsson, Krampe, and Tesch-Römer’s (1993) research on deliberate practice, we claimed that the most effective training activity in chess involves the study of games between chess masters. The chess players should try to predict the move that chess masters would select for a given game situation, and if they selected a different move, they need to analyse the game situation by planning out the consequences until they figure out why the chess master’s move was the preferable. In support of this claim, the amount of time spent on solitary study and analysis of published games between chess masters has been shown to be closely related to chess players’ tournament performance (Charness *et al.*, 1996).

In sum, our proposal for LTWM in chess focused on the acquisition of semantic representations that mediate the dynamic ability to select the best move for chess positions, which differs markedly from Gobet’s focus on mechanisms mediating memory performance. In light of the selective quotes Gobet (1998, 2000) used from our paper, we now realize that our excitement about Saariluoma’s (1989) studies led us to violate our strict focus on chess playing and the selection of chess moves. However, our discussion of Saariluoma’s studies was the only exception where we discussed results from studies of memory for chess positions.

More specifically, Saariluoma (1989) showed that chess experts were able to reproduce chess positions even if the pieces were presented auditorily one at a time ‘by listing all the pieces of the chess board with their respective locations—black knight on d4, white pawn on e6, and so on’ (Ericsson & Kintsch, 1995, p. 237). Any account of these achievements with sequential presentation of pieces, including Gobet’s, must propose that the first couple of pieces presented for a position must be

stored one by one 'at a time at the appropriate location within the retrieval structure' (p. 237). However, as more chess pieces have been presented and stored in LTM, it becomes possible to encode relations between the previously stored pieces and subsequently presented chess pieces (Ericsson & Delaney, 1998). In fact, Gobet (1998, p. 144) agreed that one of his interpretations of LTWM 'could offer a reasonable account of the data'. In a more recent series of experiments, Saariluoma and Kalakoski (1998) showed that chess masters can select chess moves of roughly comparable quality when the chess position is presented piece by piece as compared to when the complete chess position is presented visually according to the standard procedure. These findings, if they had been known to us, could have been legitimately included in our review, because it suggests a remarkable ability to reconstruct the semantic structure of the chess position mentally from information presented in a piecemeal unorganized fashion.

Comparing apples with oranges? Gobet's efforts to further specify LTWM to identify its corresponding computational mechanisms within EPAM

When two theoretical approaches differ as markedly as LTWM and TT, is it even meaningful to compare them to determine which provides the superior account? And, if it is, how can such a comparison be fairly made? Should the comparison involve memory for briefly presented regular and random chess configurations—the focus of TT, or the selection of the best move for chess positions—the focus of LTWM? As we have discussed, Gobet (2000) favours memory for chess, though these memory phenomena were deliberately excluded by Ericsson and Kintsch (1995) in their review of empirical support for LTWM:³ Gobet (2000, p. 556) acknowledged that LTWM did not aspire 'to offer a detailed theory of chess expertise but to show how LTWM could account for data from a large variety of domains' and that 'it is simply impossible to evaluate the LTWM explanation of chess expertise' unless LTWM is *further specified with many additional assumptions*. To facilitate this further specification of LTWM within the tight constraints of EPAM architecture, Gobet requests information that would be necessary to build a simulation model in EPAM where elementary processes of a given type all have the same fixed characteristics, such as duration. Gobet (2000, p. 556) asks, e.g., 'How long does it take to encode a retrieval cue?' However, as we will show in more detail later, LTWM assumes gradual speed-up of encoding and retrieval processes as a function of prior practice and accepts differences across types of materials. Consequently, Gobet's question cannot be answered in a meaningful manner for these processes within LTWM.

Another general problem concerns Gobet's efforts to translate LTWM's different associations connecting encoded information with features of the retrieval cues into the fixed organization of slots in the generic retrieval structures and templates within EPAM. Although Gobet views his continued specification of LTWM as merely adding missing pieces of information, we contend that he is enforcing assumptions

³ In a more recent paper Ericsson *et al.* (2000) proposed how experts in some, but not all domains can draw on LTWM to exhibit superior memory performance for stimuli from their domain of expertise. The critical issue of transfer of performance concerns the overlap between mechanisms mediating performance on representative (non-memory) tasks and the mechanisms needed to perform the explicit memory tasks.

that violate fundamental assumptions underlying LTWM. Even though LTWM lacks a complete computer model for chess memory, it makes basic assumptions that preclude a direct translation of LTWM into EPAM. Similarly, the translation of full-fledged computer models based on associative strength implemented in the ACT architecture (Anderson, 1983) would encounter comparable problems when translated into the EPAM IV architecture. Furthermore, in his classic book on the State, Operator, And Result (SOAR) architecture, Newell (1990) noted that given the highly constrained architecture of EPAM, it is easy to translate EPAM models into SOAR models, but he also noted that the reverse is not true. The diverse set of mechanisms of SOAR cannot be translated into EPAM.

Since Gobet and his colleagues have already explored the space of logically possible mechanisms involving retrieval structures within EPAM, Gobet (2000) apparently concludes that LTWM must resemble one of them. Within EPAM there are only two types of slotted schemas which are mutually exclusive by definition: slotted schemas with all slots—the generic retrieval structures, and slotted schemas with only few slots and mostly fixed values—the templates. As we have shown, LTWM does not match either of them.

Gobet's first published interpretation of LTWM for chess in the EPAM framework (Gobet & Simon, 1996, pp. 30–31) claimed that LTWM was mediated by generic retrieval structures, 'In a first attempt to apply the idea of retrieval structures of chess (Richman, Simon & Gobet, 1991; see also Ericsson & Kintsch, 1995, for a similar approach) we proposed a retrieval structure in the form of a single chess board with slots for storing chunks in association with the squares.'

In more recent papers Gobet (1998, 2000) has acknowledged that LTWM could potentially explain the phenomena of expert chess memory by a second alternative mechanism based on encoding of 'schemas and patterns into higher levels of the hierarchical retrieval structure' (Gobet, 2000, p. 557), and this mechanism would produce predictions that are 'consistent with masters' performance with rapid presentation times' (p. 557). With the 'schemas and patterns' interpretation, Gobet (p. 557) claims that 'all the explanatory power of the theory rests on patterns and schemas, and the concept of retrieval structure is not necessary, a traditional limited-size STM being sufficient (cf. Gobet & Simon, 1996b)'. We interpret Gobet to mean that Ericsson and Kintsch's (1995) LTWM account based on schemas and patterns can fully account for research on experts' chess memory as well as Gobet and Simon's (1996) template account without the need to rely on generic retrieval structures. However, the LTWM account, unlike the TT account, would not be able to explain how chess masters 'access rapidly the location of each piece' (Gobet, 2000, p. 557), which according to Gobet, would require LTWM to rely on generic retrieval structures, in addition.

Gobet's reasoning about LTWM appear to rely on two incorrect assumptions. First, Richman *et al.*'s generic retrieval structure is assumed to correspond to a separate retrieval-structure mechanism within LTWM. Second, templates are assumed to correspond to a separate mechanism responsible for 'generated structures in LTM' within LTWM. From our earlier review we know that generic retrieval structures and templates are mutually exclusive within EPAM. Gobet (1998) apparently believed so strongly in the correspondence between the pairs of

mechanisms discussed above that he precluded the possibility of a LTWM mechanism that integrated both functions and types of information. In fact, when Gobet (1998, p. 120) reproduced the critical Fig. 4 in Ericsson and Kintsch (1995) showing how encoded information is associated to both retrieval structures as well as elaborative associations among encoded pieces of information, he omitted a key phrase in a direct quote from Ericsson and Kintsch's caption to their Fig. 4, where we stated that the two types of information were 'establishing an integrated memory representation of the presented information in long-term memory'. The verbal description of Fig. 4 in the main text of Ericsson and Kintsch's (1995, p. 220, emphasis added) paper was even less ambiguous: 'This encoding method, which is either a retrieval structure or an elaborated memory structure *or a combination of the two (as is illustrated in Figure 4)*, determines the structure of the acquired memory skill' Gobet's (2000) current interpretation of LTWM as two independent mechanisms is also inconsistent with the repeated references to the integrated memory representation of LTWM throughout our (Ericsson & Kintsch, 1995) paper.

In his efforts to construct an interpretation of LTWM within EPAM IV, Gobet (2000) proposes that the mechanisms of LTWM correspond closely to the two types of mechanisms that he and his colleagues originally developed several years before the publication of Ericsson and Kintsch's (1995) paper. In the main review of his paper, Gobet (2000) goes on to criticize LTWM for its alleged proposal that chess experts would be able to use a generic retrieval structure of the type that Gobet (1993) originally proposed but rejected. In the next section we will show that generic retrieval structures differ fundamentally from the mechanisms proposed by Chase and Ericsson (1981, 1982) for digit-span experts and from the mechanisms that Ericsson and Kintsch (1995) proposed for LTWM.

Rejection of generic retrieval structures and 'slotted schemas' by Ericsson and Kintsch (1995)

Gobet (2000) criticizes LTWM for proposing 'a powerful retrieval structure and the capacity to make new associations into LTM' (p. 559). The problem with LTWM, in his view, is that it 'does not explain why, in spite of the powerful mechanisms and structures associated with LT-WM, [chess]masters do not recall random positions better' (p. 559). Gobet's criticisms of LTWM for these perceived shortcomings would not be valid if we can show that LTWM rejected generic retrieval structures where chess pieces or digits could be stored independently at fast rates. The evidence for this argument is as follows.

Generic retrieval structures are inconsistent with the conceptual structure of LTWM theory and the research and theoretical developments on which it is based. The mechanism of generic retrieval structure where individual digits can be independently stored in slots at a fast rate *violates all three* of Chase and Ericsson's (1981, 1982) principles of skilled memory. The first principle states that '*Experts use their knowledge structures in semantic memory to store information during skilled performance of some task*' (Chase & Ericsson, 1981, p. 159, italics in original). In their subsequent review, Chase and Ericsson (1982) claimed that digit-span expert SF, as well as DD, the digit-span expert whose performance was simulated by Richman *et al.* (1995),

semantically encoded *groups* of 3 or 4 digits. 'DD also coded virtually everything after 200 hours of practice, and the relative proportions of running times, ages, years and numerical patterns were similar to SF's' (p. 11). This is a direct contradiction of generic retrieval structures where individual digits can be rapidly and independently stored in LTM one at a time. Some of the most compelling evidence for this claim is found in the mnemonic organization of the highly accurate post-session recall (Chase & Ericsson, 1981, pp. 149–152), the dramatic effect on storage from the availability of mnemonic encoding categories (pp. 153–156), and the differential retrievability of a missing digit within an encoded digit group (pp. 167–168).

The second principle concerns the organized retrieval of information from LTM. 'In SF's case, he invented a structure that we called the *retrieval structure* for storing retrieval cues for his mnemonic codes' (Chase & Ericsson, 1981, pp. 175–176). Chase and Ericsson (1982) reviewed a large body of evidence showing that the retrieval structure encoded the location of mnemonically encoded digit-groups and *not* individual digits. Furthermore, the locations within the retrieval structure were assumed to be constructed by combinations of features. Some of the strongest evidence for this emerged from an analysis of SF's and DD's recall errors. Of particular theoretical interest, they found over 50 instances where two mnemonically encoded digit-groups had traded places within the retrieval structure. Chase and Ericsson (1982, p. 40) argued that 'the confusion errors observed between different retrieval locations', which were generally not adjacent in the digit sequence, could only be explained 'by assuming a partial loss of location features in the memory trace'. Further evidence against fixed retrieval structures was provided by SF's and DD's ability to memorize matrices of digits that did not conform to the organization of their preferred grouping of digits (cf. retrieval structures) with minimal additional practice.

The third principle of skilled memory theory proposes that rapid storage and retrieval was attained by gradual speed-up resulting from practice. Chase and Ericsson (1982, pp. 20–24) summarized the extensive evidence for SF's and DD's improved speed in encoding and self-paced memorization of the same number of digits as a function of practice, reflecting gradual learning and refinement of the mnemonic encoding and the retrieval structure: 'We assume that it takes practice, *extensive practice*, to use this retrieval system, just like any mnemonic system, and that practice involves learning to generate a set of distinctive features to differentiate one location from another. As with the mnemonic system, the more distinctive the better.' (Chase & Ericsson, 1982, p. 27)

Ericsson and Kintsch (1995) advocated a theoretical position even further removed from mechanisms involving slotted schemas. They explicitly claimed that the direct associations between the mnemonically encoded digit groups and the retrieval structure were insufficient to explain SF's and DD's performance, thus questioning the sufficiency of Chase and Ericsson's (1981) earlier hypothesis of associations between mnemonically encoded digits groups and locations within the retrieval structure. To emphasize this important point, Ericsson and Kintsch (1995) included two figures that contrasted a model based solely on retrieval cues like Chase and Ericsson (1981) with their proposed model of LTWM (p. 216 and p. 221). They reviewed empirical evidence from studies of SF and DD that show the need to

postulate additional encodings interrelating encoded digit groups to each other. For example, DD was able to memorize first one list of digits followed immediately by another list of digits, then recall the second list perfectly followed by the first list. 'Recall accuracy for the first list ranged from virtually perfect to around 70% (Ericsson and Kintsch, 1995, p. 220, and see Chase and Ericsson, 1982, pp. 39–40, for the original description of the study).

Ericsson and Kintsch (1995) took these and other empirical findings (pp. 217–220) as the point of departure for proposing encoding mechanisms based on generally accepted characteristics of associative encoding and retrieval of information in LTM that would enable expert performers to update and transform information in LTWM rapidly without compromising efficiency and reliability of retrieval. This associative account is flexible enough to accommodate encoding information about location as well as associations with other items in an integrated fashion, thus resolving the contrived problem of a forced choice between the 'retrieval structure' and 'the generated structures in LTM'.

Even without any discussion of which types of mechanisms would provide the superior account for the data on digit-span experts and other types of experts, it should be clear that the mechanisms proposed by Chase and Ericsson (1981, 1982) and Ericsson and Kintsch (1995) are completely different from both types of slotted schemas. LTWM proposes a gradual speed-up of encoding in LTM, in contrast to the fixed rates for storage in LTM and rapid storage in slots in EPAM. In LTWM, retrieval cues are acquired and refined rather than built up into fixed arrays or matrices of slots as they are in generic retrieval structures or put into fixed slots associated with particular locations in templates. More generally, LTWM theory calls into question the existence of mental slots that allow any instance of a well-defined set of items, such as digits or chess pieces, to be stored in LTM at a uniform, fixed rate.

In essence, we completely agree with Gobet's rejection of generic retrieval structures for expert memory in chess. However, the evidence that we relied on to propose LTWM leads us to go much further, to even question the empirical support for the hypothesis of slots and any type of slotted schemas—including templates as defined by Gobet and Simon (1996). In LTWM the ability to encode and associate additional chess pieces to an established complex chess configuration (fixed core of chess pieces in the template) would be based primarily on semantic relations between pieces rather than fixed spatial locations (cf. slots). We can therefore endorse Gobet's (1998, 2000) extended criticisms of generic retrieval structures for expert memory in chess. Our primary disagreement is that he did not go far enough with his criticism.

From our theoretical perspective, experts' LTWM reflects the product of a long series of gradual refinements. There is no need to propose the emergence of qualitatively new mechanisms involving fixed schemas with slots. Furthermore, our commitment to the modifiability of many aspects of cognitive processes through extended training (Ericsson & Lehmann, 1996) has led us to focus more on general constraints of associative encoding and efficient retrieval from a vast LTM than on specifying parameters for different types of memory stores. Gobet (2000) views this lack of specificity as 'vagueness' and expresses concern about the possibility of deriving falsifiable predictions for LTWM. In the next section we will discuss the

issue of the appropriate level of specificity for general theories of expert performance, and the methodological challenges posed by large individual differences in the structure of acquired skill.

Concluding remarks: toward a convergence of the two approaches

Our ultimate goal is to explain the acquisition of experts' superior performance on representative tasks. Gobet's (1998, p. 148) ultimate goal is virtually identical, though his methodology is different, since it involves 'developing a complete model of chess expertise, including problem solving, and unifying the vast body of experimental results within the study of expertise in general'. The principal difference between Gobet and us is the path we choose to achieve that goal.

Expert performance represents a unique set of empirical phenomena, where experts can consistently reproduce dramatically superior levels of performance on tasks that define expertise in the domain. Expert performance in a domain is an exceptionally stable phenomenon and represents the end product attained gradually after many thousands of hours of deliberate practice designed to improve performance on representative tasks (Ericsson, 1996; Ericsson & Lehmann, 1996). In chess, deliberate practice consists mostly of extended analyses of chess masters' published games so the less accomplished player can learn to generate the same moves as the chess masters would under similar circumstances. The task of finding the masters' 'correct' moves requires problem solving to discover the relevant aspects of a position by planning out the consequences of possible moves. This type of reasoning activity will lead to a gradual modification and improvement of LTWM to meet more effectively the demands of working memory.

Development of the specific stable structure of mediating skills, knowledge, and LTWM will depend on background knowledge and unpredictable outcomes of problem-solving episodes that will bias development of representations and knowledge. Hence, the acquired mechanisms mediating expert performance are likely to differ in their exact structure between different chess players of the same skill level. Elite chess players are well known for their different strengths and preferences, and there is evidence of differences in the mediating mechanisms and organized knowledge of chess players with same skill rating (Charness, 1981a, 1981b; de Groot & Gobet, 1996). However, the available evidence for large individual differences in mediating mechanisms due to prior knowledge and idiosyncratic preferences is strongest for memory experts. Reviews on exceptional memory (Ericsson, 1988; Wilding & Valentine, 1997) report experimental evidence for an intriguing diversity in the detailed structure of memory skill among trained digit-span experts, as well as many mnemonists and memory experts. These individual differences reflect not only variation in relevant prior knowledge, but also entrenched idiosyncratic preferences in the selection of features for retrieval cues and in the types of associations formed. No single simulation model or specific computational theory can account for all individual variation in memory performance and allow accurate predictions for performance under novel experimental conditions.

Once we accept the reality of complex and stable individual differences, it is necessary to develop theories that can account for the structure of skills and

knowledge for individual experts. It is also necessary to develop methodologies that can describe the structure of individual experts' skill, so scientists can design experiments and make performance predictions conditional on the structure of those skills. Binet (1894) pioneered these types of case studies with his analysis of the mental calculator Inaudi, where he designed a series of experiments that sequentially developed and tested working hypotheses about the structure of Inaudi's memory and skill. Subsequently, the same case-based methodology used to uncover the structure of particular individuals' cognitive abilities and skills has been used to study numerous memory experts, such as Professor Ruckle (Müller, 1911, 1917), subjects S (Luria, 1968) and VP (Hunt & Love, 1972), just to cite some of the classics (see Ericsson, 1985; Wilding & Valentine, 1997, for reviews). It was this great diversity in the detailed mechanisms of memory skill of different individuals with exceptional memory that led Chase and Ericsson (1981, 1982; Ericsson & Chase, 1982) to focus on general and generalizable mechanisms of skilled memory.

More generally, an ultimate general theory describing complex skills and expert performance will probably not be at the level of detailed elementary processes, but closer to the level of mechanisms described in Ericsson and Kintsch (1995), which can be induced and abstracted from case descriptions. The additional advantage of a general theory is that it allows scientists committed to different architectures, such as SOAR, EPAM, ACT, and even connectionist frameworks, to apply ideas about the mechanisms mediating LTWM. In fact, Altmann and John (1999) and Young and Lewis (1999) have been able to make important contributions relating LTWM to mechanisms explicated within the SOAR architecture.

A completely different path toward an understanding of chess expertise is advocated by Gobet and his colleagues who build explicit simulation models within the EPAM architecture. This approach seeks out the simplest phenomenon that can reveal the basic structure of the human system while still reflecting large individual differences in expertise, which in this case is recall of presented chess stimuli. Within the tightly constrained framework of EPAM, Gobet and Simon (1996) developed the most parsimonious computational mechanisms into a full-fledged simulation model to reproduce the average memory performance of chess players across different levels of skill. Based on actual simulations, they showed that a chunking mechanism and a generic retrieval structure with slots representing the squares of the chess board were unable to explain all aspects of the observed memory performance. In order to explain the superior performance of chess masters they proposed that masters have acquired templates, which correspond computationally to large chunks with slots where chess pieces can be rapidly stored only in specified squares on the chess board.

The hypothesized templates have a more complex structure than Chase and Simon's (1973) patterns and chunks and they are far more constrained by extensive knowledge about chess playing. Gobet and Simon (1998, p. 229) stated that the 'templates contain pointers to symbols representing plans, moves, strategic and tactical concepts, as well as other templates' and estimate that 'A grandmaster or master holds in memory literally thousands of such patterns [templates]' (Gobet & Simon, 1996, p. 31). Although TT may, in principle, offer a bridge between the superior memory of masters and master-level chess playing, there is no firm experimental evidence to support such claims. All we know at this point is that

templates offer a plausible computational mechanism to explain skill differences in average recall of chess positions. From our perspective it would be very important to identify and fully describe a number of specific templates used by a few chess masters and then demonstrate that these templates mediate performance on the move selection tasks as well as memory for the presented chess positions. It would then be possible to design experiments that could test hypotheses about the structure of distinct templates. Would the chess masters' performance be consistent with templates in the form of fixed schemas that contain predetermined slots to store chess pieces in some but not other locations of the chess board? Or would an account based on the generation of new structures in LTM relying on associations between schemas and chess pieces better explain memory of the presented chess positions? Only extended research can provide the necessary experimental evidence to assess the best theoretical accounts of master-level chess playing.

In conclusion, the starting-point for Gobet and Simon's (1996) TT and our LTWM could hardly have been more different. Yet, both approaches offer different methodologies that should complement and support future research on understanding expert performance in chess. Hopefully, our paths and approaches will eventually converge so we can address the challenge of understanding the complex mechanisms that mediate expert performance in chess from multiple perspectives in a more collaborative fashion.

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