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Mental Imagery and Chunks: Empirical and Computational Findings

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Abstract

To investigate experts' imagery in chess, players were required to recall briefly-presented positions in which the pieces were placed on the intersections between squares (intersection positions). Position types ranged from game positions to positions where both the piece distribution and location were randomized. Simulations were run with the CHREST model (Gobet & Simon, 2000). The simulations assumed that pieces had to be centered back one by one to the middle of the squares in the mind's eye before chunks could be recognized. Consistent with CHREST's predictions, chess players (N = 36), ranging from weak amateurs to grandmasters, exhibited much poorer recall on intersection positions than on standard positions (pieces placed on centers of squares). On the intersection positions, the skill difference in recall was larger on game positions than on the randomized positions. Participants recalled bishops better than knights, suggesting that Stroop-like interference impairs recall of the latter. The data supported both the time parameter in CHREST for shifting pieces in the mind's eye (125 ms per piece) and the seriality assumption. In general, the study reinforces the plausibility of CHREST as a model of cognition.

Mental Imagery and Chunks: Empirical and Computational Findings

Ever since Binet's (1894) work on blindfold chess, psychologists have investigated the role of mental images in expert problem solving (e.g., Simon, 1978; Larkin, Mc Dermott, Simon, & Simon, 1980; Larkin & Simon, 1987; Paige & Simon, 1966; Tabachnek-Schijf, Leonardo, & Simon, 1997). The concept of chunking has also been shown to be essential in experts' perception, memory, and problem solving (e.g., Campitelli & Gobet, 2005; Chase & Simon, 1973a, 1973b; De Groot, 1978; Kalakoski, 2006; Saariluoma, 1995). However, despite the wealth of research investigating chunking and mental imagery as separate topics, less is known about the interaction between chunking and mental imagery. The goal of this article is to provide experimental evidence about this interaction, and to test the predictions of a well-established computational theory of expertise.

Mental Imagery in Chess

Chase and Simon's (1973b) influential chunking theory proposed that pattern recognition explains (a) how experts show a remarkable memory for domain-specific material and (b) how search can be carried out in the mind's eye, where future positions are imagined. According to these authors, the mental processes used in chess playing are similar to those identified in mental rotation and other imagery tasks (Shepard & Cooper, 1982). Chase and Simon's ideas about the mind's eye have not been thoroughly tested, but the existence of chunks is well established (Chase & Simon, 1973b; Gobet & Clarkson, 2004; Gobet & Simon, 1998).

Empirical evidence on imagery in chess comes from studies on blindfold chess (e.g., Saariluoma & Kalakoski, 1997) and studies that have attempted to measure the time needed to move a piece in the mind's eye (Church & Church, 1977; Milojkovic, 1982; Gruber, 1991; Waghorn, 1988). In general, these experiments have confirmed that (a) chess memory has a significant visuo-spatial component, and (b) mental imagery has an important role in chess. For example, Bachman and Oit (1992) studied mental imagery using a variation of Attneave and Curlee's (1983) moving-spot task. Chess players and non-players were presented with either an 8 x 8 grid or a chessboard. They were then required to close their eyes, listen to a sequence of instructions about the moves of the spot or a chess piece (up, down, right or left), and imagine following the spot or piece at it moves. At the end of the sequence of moves, participants had to indicate the end position of the spot or the piece. There were no skill differences in the moving-spot (8 x 8 grid) condition, but non-players made more errors than chess players in the moving-chess piece (chessboard) condition. Furthermore, in the latter condition, skilled players tended to show Stroop-like interference when required to mentally shift a piece in an atypical fashion. For example, chess players found it difficult to imagine a Bishop moving horizontally (which is incongruent with its typical diagonal movement).

As noted above, mental imagery played an essential role in Chase and Simon's (1973a; 1973b) influential chunking theory. More recently, the mechanisms of pattern recognition, forward search and mental imagery have also been integrated in a modification of the chunking theory, the template theory (Gobet & Simon, 1996b). The template theory has led to two related computational implementations: one aimed as simulating search behavior (SEARCH: Gobet, 1997), and the other predominantly aimed at simulating perception, learning, and memory (CHREST: De Groot & Gobet, 1996; Gobet et al., 2001; Gobet & Simon, 2000; Gobet & Waters, 2003).

CHREST

CHREST is a model of learning and expertise that has accounted for data on chess perception, learning, and memory (De Groot & Gobet, 1996; Gobet et al., 2001; Gobet & Simon, 2000; Gobet & Waters, 2003), the use of diagrammatic information in physics (Lane, Cheng, & Gobet, 2000), the acquisition of vocabulary (Jones, Gobet, & Pine, 2005), and the acquisition of syntactic structures (Freudenthal, Pine, & Gobet 2005; Freudenthal, Pine, & Gobet, 2006). CHREST, written in Common Lisp, can be obtained from the second author.

CHREST consists of four main components: a simulated eye, a long-term memory (LTM), where chunks are stored, a visual STM with a capacity of 3 items, and a mind's eye system (see Figure 1 for overview). Briefly, CHREST is a self-organizing, dynamical system, in which chunks are accessed by traversing a discrimination net (see De Groot & Gobet, 1996, for details). .A discrimination net is a treelike structure consisting of a set of nodes (chunks) connected by links. The links have tests, which are applied to check features of the external stimuli.

There has been debate as to how chunks are coded in chess. Some authors (e.g., Simon & Gilmartin, 1973) have proposed that chunks encode information about location (localization assumption). Others (e.g., Holding, 1985) have suggested that chunks do not encode location information, but only the pattern of relation between pieces. Thus the same chunk could be used for coding a pattern of pieces on the bottom left of the board, or the top right of the board. Experiments where boards where modified by translation (Saariluoma, 1994) or mirror image (Gobet & Simon, 1996a) supported the localization assumption.

Chunks that are often recognized evolve into more complex data structures, known as *templates*, which have *slots* allowing variables to be instantiated rapidly (filling in information into a template slot takes 250 ms). In particular, information about piece location, piece type, or chunks can be (recursively) encoded into template slots. Slots are created at chunks where there is substantial variation in squares, pieces, or groups of pieces in the test links below. In addition to slots, templates contain a *core*, basically similar to the information stored in chunks. Chunks and templates can be linked to other information stored in LTM, such as moves, plans, and tactical motives (see Ferrari, Didierjean, & Marmèche, 2006, for data supporting for the idea that chunks are associated with possible moves).

Eye movements are directed from a combination of acquired knowledge, mediated by the structure of the discrimination net, and heuristics (e.g., heeding a square attacked by the piece located on the currently fixated square) (see De Groot & Gobet, 1996, for details).

The Mind's Eye in CHREST

The mind's eye construct in CHREST is similar to Kosslyn's (1994) visual buffer and Baddeley's visuo-sketchpad (Baddeley, 1986; Logie, 1986). It is specified in less detail than the former, in particular with respect to anatomical and neural considerations, but with more detail than the latter, which lacks a computational implementation. The architectural assumptions in CHREST resemble those in other models developed by Simon (in particular, CaMeRa, Tabachnek-Schijf et al., 1997, and EPAM-IV, Richman, Staszewski, & Simon, 1995), and can be traced back to Chase and Simon's (1973a) construct of the mind's eye.

The mind's eye stores perceptual structures, both from external inputs and from memory stores, for a short time. The visuo-spatial information stored there can be subjected to visuo-spatial mental operations. In the mind's eye, the internal representation of the external scene is encoded as a network of nodes and links (e.g., Larkin & Simon, 1987; Newell & Simon, 1972). Note that the information in the mind's eye abstracts much from perceptual information impinging the retina, which makes the task of pattern recognition mechanisms easier than with external perceptual information.

A recurring feature of CHREST, influenced by Simon's earlier work (e.g., Simon, 1969), is the emphasis of cognitive limitations. There are limitations in memory capacity (visual STM can hold only three items) and learning rates (it takes about eight seconds to create a new chunk). Another limitation is that information in the mind's eye decays rapidly, within around 250 ms (Averbach & Coriell, 1961; Kosslyn, 1994).

In addition, CHREST makes several assumptions about the processes that are carried out in the mind's eye. For chess, these processes include the time to move a piece mentally; for problem solving in physics, these processes include instructions for drawings lines or more complex geometric figures (Lane et al., 2000). These mental processes are assumed (a) to take a definite amount of time (see below) and (b) to be carried out serially ("seriality assumption"; see Kosslyn, Cave, Provost, & Von Gierke, 1988, for data supporting the assumption that mental images are generated serially). In addition, CHREST includes mechanisms linking LTM, STM, and the mind's eye. It is assumed that learning leads to the creation of chunks in LTM. When a chunk is elicited, either by external or internal information, a pointer to it is placed in STM.[1] Concurrently, the visuo-spatial information referred to in LTM by this pointer is unpacked in the mind's eye. As information in the mind's eye fades rapidly, it needs to be refreshed regularly.

Overview of the Study

Several assumptions behind CHREST have been directly tested (Gobet & Simon, 2000; Gobet & Jackson, 2002; De Groot & Gobet, 1996). However, there have been no experimental tests of CHREST's assumptions and mechanisms about imagery. Using the few experiments available (noted above), De Groot and Gobet (1996, *p*. 236) proposed two parameters for the time to move pieces in the mind's eye: the *base* parameter refers to the time needed to start the process of generating a move, while the *square* parameter estimates the time needed to move a piece over one square in the mind's eye. With players who are not novices, the base parameter was set to 100 ms and the square parameter was set to 50 ms. The present study directly tests the validity of these parameters.

In addition, a strict interpretation of the localization assumption implies that decoupling pieces from their natural ground (the chessboard), for example by shifting them diagonally, should make the access to chunks harder. This is because pieces would have to be individually shifted back to the center of their squares in the mind's eye to enable access to chunks. An alternative prediction would be that the relations between pieces are identifiable without reference to the ground (the board), and thus no shifting back is necessary. To decouple figure and ground, we created positions where the pieces were placed at the intersection of squares (rather than being placed in the middle of the squares). We will call these stimuli "intersection positions." If chunks are recognized without the need to re-center pieces, then recall on the intersection positions should not differ from that on the standard positions. If, on the other hand, pieces need to be re-centered before chunks can be recognized, then there should be a decrease in performance. The size of this decrease can be predicted by running simulations with CHREST.

Two additional variables were manipulated. First, positions with different levels of structure were used (from game position to fully randomized positions). This manipulated the ease by which chunks could be accessed in LTM. Second, different skill levels were used, which was assumed to control for the number of chunks held in LTM.

In the remainder of the paper, we first present a simulation that assesses recall for different position types across different skill levels (net sizes) (computer simulation 1). We then present human data that assesses recall on the same position types (human study 1). This is followed by an additional human study that assesses the specificity of the effects observed in human study 1 (human study 2), and an additional simulation that examines the seriality assumption of the mind's eye (computer simulation 2).

Computer Simulation Study 1

Learning Phase

During learning, the program scans a large number of positions. For each position, the simulated eye is moved around the board, and patterns within CHREST's visual field (defined as +/- 2 squares from the fixation point) are sent as input to the discrimination net, where the learning mechanisms of familiarization, discrimination, and template formation are applied (see de Groot & Gobet, 1996, and Gobet & Simon, 2000, for details on the model).

Testing Phase

Encoding. The model moves its simulated eye around the board, and attempts to recognize chunks (or templates). The simulations reported below all used a presentation time of 5 s. We used the same version of CHREST used by Gobet and Simon (2000) and Gobet and Waters (2003). For the simulation of the intersection positions, we extended the model by adding as few assumptions as possible related to the time needed to carry out operations in the mind's eye. The augmented model attempts to memorize the intersection positions by serially moving pieces (up to 3) within the visual field to the center of the square in the mind's eye and then sorting the (shifted) pattern of pieces through the discrimination net.

Figure 2 illustrates the processes involved in shifting a group of three pieces in the mind's eye. It is assumed that the internal representations of the objects present in the external display (pieces on the intersection board) maintain a high activation as long as one is looking at these objects (cf. Kosslyn, 1994). By contrast, after shifting, the imaged (shifted) objects are subject to decay. Shifting the object or recognizing a chunk in the mind's eye resets the level of activation of these objects to high. As with chunk recognition from an external input, recognition from the mind's eye leads to a pointer being placed in STM (see above).

At time 0, the three pieces are perceived in the external display. At time 125 ms, the bishop has been shifted, and its activation is high. At time 250 ms, the rook has been shifted (high activation); in the meantime, the activation of the bishop has decayed to medium. At time 280 ms, a chunk (rook + bishop) has been recognized and a pointer to it entered into STM, and the activation of its components is set to high. Sorting information in the discrimination network has a base cost of 10 ms, plus 10 ms per item, giving a total of 30 ms. At time 405 ms, the knight has been shifted, and the activation of the chunk (rook + bishop) has decreased to medium. At time 445 ms, a three-piece chunk (rook + bishop + knight) has been recognized and a pointer to it has replaced the previous pointer in STM.

Recall. During recall, the model (re-)places pieces sequentially using the information provided by the chunks in STM. Possible conflicts (e.g., two chunks propose that two different pieces are placed on the same square) are resolved in sequence, based on the frequency with which each placement is proposed. The pieces were always re-shifted to the appropriate intersection (SE corner). This re-shifting assumption was predicated on the assumption that the direction of re-shifting was not problematic for humans. As noted below, participants learned the direction that pieces were shifted during practice, and the presence of pieces on the "back" White row (but not the "back" Black row) gave additional visual cues on every trial. In addition, the software assisted in piece re-placement (clicking a piece on a square at a location sufficiently close to the intersection placed the piece at the intersection) (this was not simulated in the model).

For the time needed to shift a piece (transition-time), we used the parameters already in CHREST for the time to move a piece diagonally for players who are not novices (100 ms as base time, and 50 ms for each square traversed). We therefore assumed that, to re-center the pieces in the intersection positions, it takes the base time plus half of the time to traverse a square diagonally, i.e., 125 ms in total. This was true for discrimination nets of all sizes.

Method

Materials

In common with Gobet and Waters (2003), we used five position types. Game positions were taken from master games without any change. Random positions were constructed by randomly reassigning the pieces of a game position to new squares. In "truly" random positions, not only the location of the pieces was randomized, but also the distribution of pieces (e.g., there could be 12 white kings in a position, contrary to the standard chess rules). One-third and two-third truly random positions were positions where 1/3 and 2/3 of the pieces were truly randomized.

The testing stimuli were created following the procedure described in Gobet and Waters (2003). Five hundred stimuli were selected using random sampling without replacement from a database of 3,100 positions. These positions were taken from master-level games, after about 20 moves. In the game condition, the stimuli were kept unmodified. The algorithms described in Gobet and Waters (2003) were used to generate the four types of random position. The same procedures were used to generate the intersection stimuli, except that the end product was manipulated by shifting all pieces to the south-east corners of the squares. Examples of all position types for the intersection positions are shown in Figure 3a.

Procedure

To obtain quantitative predictions, we used the same nets as those chosen by Gobet and Waters (2003). The selection procedure was as follows. During learning, the program scanned a database of about 50,000 positions. The positions were middle-game positions, taken from master-level games played in the last fifty years. This resulted in an original pool of 16 nets, from which four nets (with 1,010, 3,008, 15,003, and 300,009 chunks) were chosen. These were selected as they most closely matched the mean recall of the four groups of human subjects on standard game positions. To facilitate interpretation of data analyses, the 300,009-chunk net was considered to have a rating of 235.6 in "human" units (the mean skill rating of our top group of humans; see Gobet and Waters, 2003, for further detail on this strategy).[2] The 15,003-chunk net was considered to have a rating of 201.2 in human units (the mean skill rating of our second group of humans), the 3,008-chunk net a rating of 150.9, and the 1,010-chunk net a rating of 112.3. The simulations below are based on the recall of 500 positions of each type. Each position was presented for a simulated time of 5 s.

Data Reduction and Analysis

All statistical analysis was carried out using SAS (SAS/STAT Software, 1997). To test differences in recall on the standard and intersection positions, we used a 2-way Layout (Standard vs. Intersection) by Position Type (5 levels: game, 1/3, 2/3, random, 3/3) ANOVA. On the intersection positions, we used linear regression to predict recall performance (the dependent variable) from Net Size (the independent variable, expressed in human units). We did this for each position type (game, 1/3, 2/3, random, 3/3) separately. We used the unstandardized parameter estimates from these models as an index of the Net Size effect, and used the *p* value of the parameter estimate to determine whether the slope was significantly different from zero. To determine whether the Net Size effect on one position type was steeper than that on other position types, we used regression analysis (proc glm in SAS) to test for Net Size by Position Type interactions, where Position Type was entered as a repeated measures variable. To compare the Net Size effect on the game positions with the mean Net Size effect on the other positions, we used the helmert comparison option.

Results and Discussion

Table 1 shows recall as a function of Net Size and Position Type, for both standard (left side of table) and intersection positions (right side of table); for the latter, we focus for the time being on the serial transition type (upper row). Recall was clearly worse on the intersection positions. A 2-way Layout (Standard vs. Intersection) by Position Type (5 levels) ANOVA yielded a main effect of Layout, $F(1, 3) = 29.9$, $p < .05$, and a main effect of Position Type, $F(4, 12) = 40.3$, $p < .0001$. There was also a Layout by Position Type interaction, $F(4, 12) = 15.8$, $p < .0001$, indicating that deterioration in recall on the intersection positions was moderated by position type. Inspection of Table 1 indicates that the deterioration in recall on the intersection positions (vs. standard positions) was most pronounced on the game positions. This is because the model is slowed down by having to carry out the mental transformations. This prevents it from sampling a sufficient number of squares to access large chunks.

On the intersection positions (right side of Table 1), the data indicate that the effect of Net Size is more robust on the game condition than on the randomized positions. The 300k net achieved 44.8% recall of the game positions, whereas the 1k net only achieved 23.7% recall. In contrast, on the 3/3 positions, the difference in recall was much smaller (10.7% vs. 4.1% for the 300k and 1k net, respectively). Numerical estimates of the Net Size effects were: game = 0.173; 1/3 = 0.092; 2/3 = 0.050; random = 0.051; and 3/3 = 0.057. The Net Size effects were all significantly differently from zero ($p < .05$), except for on the random positions, where the effect was a trend ($p = .058$). Statistical comparison of the Net Size effect on the game, 1/3, 2/3, random, and 3/3 position types indicated a robust Net Size x Position Type interaction, $F(4, 8) = 66.1$, $p < .001$. The effect of Net Size was significantly larger on the game positions than on the mean of the other position, $F(1, 2) = 571$, $p < .005$.

In summary, four CHREST nets were created, corresponding to four levels of chess skill. The program then recalled briefly-presented positions (either standard or intersection) that ranged from game positions to fully random positions. Recall was poorer on the intersection positions than on the standard positions, particularly on the game positions. On the intersection positions, the skill effect was larger on the game positions than on the randomized positions.

Human Study 1

As noted earlier, this experiment was part of a larger study where standard positions were also presented. The main focus of Gobet and Waters (2003) was to test the conflicting predictions of CHREST and the Constraint Attunement Hypothesis (Vicente & Wang, 1998) on the role of constraints in expert memory. In the current study, the aims of the study were as follows. First, we wanted to test CHREST's predictions on recall in the intersection positions. Thus, we examined whether (a) recall on the intersection positions was impaired (vs. recall on standard positions); (b) the effects of Skill were larger on the game positions than the randomized positions; and (c) the effects of Skill were significant on each position type.

Second, given that the intersection task likely involves imagery, we also examined whether we could detect Stroop-like interference effects that had been previously observed using a different imagery task (Bachman & Oit, 1992). To do so, we compared recall of bishops and knights. These two pieces are considered to be of equal value (3 points), and therefore are matched in terms of "economic" salience on the chessboard. (It would be difficult to compare recall of rooks and bishops, because the former have greater value and might attract focus for this reason.) Critically, the bishop moves along a diagonal line, and so mental imagery on the intersection task is congruent with its typical movement. In contrast, the knight does not move diagonally, and so mental imagery with this piece is less congruent with its typical movement[3]. Thus, if mental imagery were involved, we would expect participants to recall bishops better than knights (Bachman & Oit, 1992).

Method

Participants

Thirty-six participants (mean age = 28.6, *SD* = 8.0) completed the study; they were the same participants who took part in the study reported by Gobet and Waters (2003), and the data reported here was obtained from the 2003 study. The top group ("grandmasters", *n* = 7) were players with BCF (British Chess Federation) ratings of above 225. The second group ("masters/experts", *n* = 12) had BCF ratings between 175 and 224. This group contained 3 IMs, 1 FIDE master, 1 female GM, 1 female IM, and 6 experts. The third group ("Class A/B players", *n* = 10) consisted of players with ratings between 125 and 174; these players are considered moderate to strong club players. The final group ("Class C/D players", *n* = 7) contained players with ratings less than BCF 125; while these players are considered weak club players, they are far from being novices. Further details of the participants and experimental procedures are available in Gobet and Waters (2003).

Materials.

Chess stimuli. The same five types of position were used as in the simulation study (see Figure 3a). Twenty-five positions (with an average of 25 pieces) were taken from master games after about 20 moves, and were randomly assigned to one of the five types of intersection positions for each player. There were thus five positions in each condition.

Presentation software and hardware. Chess stimuli were presented on a portable Apple MacIntosh computer using specialized software for presenting chess stimuli and recording responses (see Gobet & Simon, 1998, for a detailed description of the software used). Participants were required to use a mouse to select pieces, move pieces onto squares (standard positions) or intersections between squares (intersection positions), and delete pieces (Figure 3b). To go on to the next trial, the subject pressed an OK button on the top left corner of the computer screen.

Visual memory test. All participants completed a test of visual memory (the Shape Memory Test (MV-1) of the Educational Testing Service [ETS] Kit of Factor-Referenced Cognitive Tests; Ekstrom, French, Harman, & Derman, 1976).

Procedure

Participants completed the visual memory test, followed by the recall task. On each trial, a position was presented for 5 s. The screen then was blank for 2 s, and then an empty chess board appeared. The participants were instructed to try to recall the positions as completely and as accurately as possible. On standard positions, the pieces were presented in the center of the squares, and participants were instructed to replace the pieces in the center of the squares (Figure 3b, upper panel). On intersection positions, the pieces were presented at the intersection of the squares (always in the south-east direction), and participants were instructed to replace the pieces at the intersection of the squares (Figure 3b, lower panel). In this condition, the software allowed the pieces at the intersection of squares (but not at the center of the squares). On each trial, participants had unlimited time to make their response.

The presentation of standard and intersection positions was blocked, and the order of presentation counterbalanced over participants. Within each block (standard, intersection), the 20 random positions (4 position types x 5 stimuli) were first presented in a different random order for each subject. The 5 game positions were then presented, also in a different random order for each subject. Participants had two practice trials on random positions, and one practice trial on game positions.

Data Reduction and Analysis

To test differences in recall on the standard and intersection positions, we used a 2-way Layout (Standard vs. Intersection) by Position Type (5 levels: game, 1/3, 2/3, random, 3/3) ANOVA. On the intersection positions, to obtain estimates of the skill slopes, we performed regressions in which recall performance (the dependent variable) was predicted from BCF rating, age and visual memory (VM) entered together (the independent variables).

(Results of regression analyses for recall on the standard positions are reported in Gobet & Waters (2003)). As an index of chess skill, we used participants' ratings in the BCF rating list at the time the data were collected. Following Gobet and Waters (2003), we also included Age and VM in all the models. Age has been shown to be an important variable in chess memory (Charness, 1981a, b), and VM has been associated with recall performance on this task (Waters, Gobet, & Leyden, 2002).

Separate regressions were carried out for each position type. The unstandardized parameter estimate for BCF rating provided our estimate of the skill slope, and the *p* value of this statistic determined whether it was significantly different from zero. (To facilitate direct comparisons between the coefficients, we also report the standardized parameter estimates). To determine whether the skill slope on one position type was steeper than that on another position type, we tested BCF rating by Position Type interactions, where Position Type was entered as a repeated measures variable with five levels. Since the model makes directional and unambiguous predictions about recall performance on all conditions, we used 1-tailed tests for all analyses of skill effects on recall; 2-tailed tests were used for effects of age and VM on recall, and for all other analyses.

To test differences in recall of bishops and knights on the intersection positions, we used a Piece (Bishop vs. Knight) by Position Type (5 levels: game, 1/3, 2/3, random, and 3/3) ANOVA on percentage recall of these two pieces. We examined the effects of skill, age, and BCF rating by adding these variables as independent variables to a regression model (Piece and Position Type were entered as a repeated measures variable with 2 and 5 levels respectively).

Results

% Correct Recall

Table 1 shows the mean recall by skill level and position type, for both standard (left side) and intersection positions (right side). Across all skill levels, recall was worse on the intersection positions. A 2-way Layout (Standard vs. Intersection) by Position Type (5 levels)

ANOVA yielded a large main effect of Layout, $F(1, 31) = 82.5$, $p < .0001$, and Position Type, $F(4, 140) = 193.9$, $p < .0001$. There was also a Layout by Position Type interaction, $F(4, 140) = 38.8$, $p < .0001$, indicating that deterioration in recall on the intersection positions was most pronounced on the game positions (Table 1). However, follow-up analyses revealed that the effect of Layout was significant on all Position Types (all *p*s < .01).

Table 2 reports the results of regression analyses on individual position types (% correct recall, intersection only). BCF rating significantly predicted recall only on the game positions; on these positions an increase of 100 BCF grading points (e.g., the difference between an average club player and a grandmaster) yielded an increase of about 10% in recall, which corresponds to about two and a half pieces. VM significantly predicted recall on three of the non-game positions. Age tended to be negatively associated with recall, but only significantly so on the 1/3 randomized positions.

Using general linear modeling (proc glm in SAS), we also conducted an omnibus regression analysis in which all five position types were included as a repeated measures variable with 5 levels. This analysis revealed a significant effect of VM, $F(1, 32) = 6.65$, $p < .05$, but no VM by position type interaction $F(4, 128) = 0.24$, $p > .90$, indicating that the association between VM and recall did no differ across position types. There was also a significant effect of BCF rating, $F(1, 32) = 3.05$, $p < .05$ (1-tailed), and a significant BCF rating by position type interaction $F(4, 128) = 2.13$, $p < .05$ (1-tailed), indicating that the association between BCF rating and recall was significantly moderated by position type. As illustrated in Table 2, BCF rating predicted recall on the game positions, but not the randomized positions. There was a trend toward a significant effect of age, $F(1, 32) = 3.55$, $p = .07$, and no age by position type interaction $F(4, 128) = 0.57$, $p > .60$. As expected, there was also a main effect of position type, $F(4, 128) = 97.9$, $p < .001$.

Bishop vs. Knight Recall

Table 3 shows the mean percent recall of bishops and knights in intersection positions by skill level and position type. A Piece (Bishop vs. Knight) by Position Type (5 levels) ANOVA conducted on percent correct recall (on the intersection positions) revealed the expected main effect of Position Type, $F(4, 140) = 10.0$, $p < .0001$. Importantly, there was also a main effect of Piece, $F(1, 35) = 16.9$, $p < .001$, indicating that, averaged over all positions types, participants recalled Bishops ($M = 11.9\%$, $SE = 0.93$) significantly better than Knights ($M = 8.7\%$, $SE = 0.90$) on the intersection positions. This main effect was qualified by a significant Piece by Position Type interaction $F(4, 140) = 14.9$, $p < .0001$. Follow-up analyses indicated that participants were better at recalling bishops (vs. knights) on the (intersection) game and 1/3 positions (*p*s < .0001), but not on the other position types (all *p*s > .05). For comparison purposes, we also conducted a Piece (Bishop vs. Knight) by Position Type (game vs. 1/3 position) ANOVA on percent correct recall on the standard positions. This revealed no main effect of Piece, $F(1, 35) = 0.03$, $p > .8$, indicating that participants were not better at recalling Bishops (vs. Knights) on standard (non-shifted) game and 1/3 positions.

A regression analysis on recall of bishops and knights (on the intersection positions) that incorporated BCF rating, age, and VM as independent variables yielded the expected main effect of BCF rating, $F(1, 32) = 6.74$, $p < .01$, and BCF rating by Position Type interaction, $F(4, 128) = 4.22$, $p < .01$, thereby paralleling the results reported above (for all pieces). There were no significant interactions involving Piece (all *p*s > .05), indicating that the effects of Piece noted above were not significantly moderated by BCF rating.

Errors of Commission

Errors of commission occur when pieces are placed on incorrect squares. Over all participants, the mean number of errors of commission on the (intersection) game, 1/3, 2/3, random and 3/3 positions was 5.13 ($SD = 3.70$), 3.98 ($SD = 3.98$), 4.70 ($SD = 4.63$), 4.61 ($SD = 4.49$), and 4.74 ($SD = 4.54$), respectively. There were no significant effects of BCF rating, age, or VM. An omnibus regression incorporating position type as a repeated measures variable also yielded no significant effects of BCF rating, age or VM.

We examined errors of commission on bishops/knights on intersection positions. We reasoned that if participants were shifting the pieces in the mind's eye along the SE-NW diagonal, participants would be more likely to misplace bishops on the intersections SE and NW of the target intersection than on the intersections SW and NE of the target intersection. Averaged over all positions types, the mean percentage of bishops misplaced on intersections SE/NW of the target intersection was 1.89 (SD = 1.97), and the mean percentage of bishops misplaced on intersections SW/NE of the target intersection was 1.25 (SD = 1.90). This difference approached significance, F (1, 35) = 3.68, p = .06. The mean percentage of knights misplaced on intersections SE/NW and SW/NE of the target intersection was 1.54 (SD = 2.05) and 1.46 (SD = 2.53) respectively. This difference was not statistically significant.

Discussion

Recall was impaired on the intersection positions compared to the standard positions (Table 1). Consistent with CHREST's predictions, this impairment was especially pronounced on the intersection game positions (significant Layout by Position Type interaction). Our working assumption is that human processing is slowed down by the processes of carrying out mental transformations to re-center the pieces, which impairs the ability to access chunks/templates in the intersection game positions.

Skill effects were present on the intersection game positions, but not on the other positions (significant Skill by Position Type interaction). This interaction is consistent with CHREST's predictions. Skill was not associated with errors of commission, meaning that the superior recall of better players did not come at a cost of more errors of commission. This means that the skill effect was unlikely to be due to more extensive guessing by the better players.

Participants were better at recalling bishops than knights on the intersection positions (but not the standard positions). We interpret this result to indicate the presence of mental imagery: the mental transformations were easier for the bishops than the knights. In addition, participants tended to be more likely to misplace bishops on the intersections SE and NW of the target intersection than on the intersections SW and NE of the target intersection. This pattern of results is consistent with the use of mental imagery along the SE-NW diagonal, and provides some additional support for the presence of imagery.

The evidence for imagery was stronger on the game and 1/3 intersection positions than on the other positions (significant Piece by Position Type interaction) (Table 3). Nonetheless, we do not rule out the possibility that some imagery was involved in all the positions. Note that mean recall of bishops/knights is poor (M = 8.7%) on the three most randomized positions (Table 3). Speculatively, on the more random positions, so few bishops/knights get shifted and actually get encoded in STM (as a piece or as part of a chunk) that the bishop vs. knight effect may be less visible in those positions.

Human Study 2

Our working assumption is that the results obtained in human study 1 reflect imagery processes. For example, we assume that the poorer recall on the intersection (vs. standard) positions reflects the costs incurred by shifting the pieces in the mind’s eye before recognition can occur (on the intersection positions). The superior recall of bishops vs. knights provides more direct evidence that imagery plays a role. Nonetheless, it is also possible that the results in human study 1 reflect lower-level processes. For example, the unfamiliar intersection positions may require more or longer eye fixations than the standard positions. The effect of layout (in the human data) may therefore reflect the difference in how much information the participants are able to extract during the 5-s presentation. Thus, the results in human study 1 may reflect differences in visual processing, in addition to, or instead of, mechanisms of the mind's eye.

To address the role of lower-level factors, we re-examined recall data from an experiment that had high perceptual demands. Gobet and Simon (2000) included one condition in which participants had to recall positions which were presented for only 1 s. In this condition we assume that participants would have experienced difficulty in perceiving the entire board. Both game and random positions were presented, using the standard layout (there were no intersection positions). If the superior recall of bishops over knights in the intersection condition was due to low-level processes, then the same superiority should be found in the 1-s condition. On the other hand, if this superiority was due to mental imagery, it should not be present in the 1-s condition, as there is no need to re-center the pieces in the mind's eye.

Method

Participants

Twenty participants (mean age = 32.9 years, *SD* = 11.6) drawn from Gobet and Simon (2000) completed a 1 s recall task. Their mean Elo rating was 2131 (*SD* = 256). Further details of the participants and experimental procedures are available in Gobet and Simon (2000).

Results

Mean recall of bishops/knights on the standard game and random positions is shown in Figure 4 (bottom panel). A repeated measures ANOVA revealed the expected main effect of Position, $F(1, 19) = 11.7$, $p < .01$, indicating that recall was better on game positions than random positions. There was no main effect of Piece, $F(1, 19) = 2.32$, $p > .1$, indicating that participants were not better at recalling bishops than knights. There was no Piece by Position interaction, $F(1, 19) = 1.46$, $p > .1$. A regression analysis that incorporated Elo rating as an independent variable yielded the expected main effect of Elo rating, $F(1, 18) = 22.6$, $p < .001$, indicating that more skilled participants exhibited generally superior recall, and an Elo rating by Position Type interaction, $F(1, 18) = 24.0$, $p < .001$, indicating that skill effects were larger in the game positions than the random positions (i.e., the typical finding). There were no interactions between Piece and Elo rating (all ps > .1).

Discussion

Recall in the 1-s presentation condition exhibited the expected Skill by Position Type interaction. However, in contrast with the results for the 5-s intersection position, participants were not better at recalling bishops than knights. If anything, they were (non-significantly) better at recalling knights. Thus, the effect of Piece is specific to the 5-s intersection condition (middle panel, Figure 4), and does not appear either on the 5-s standard positions (upper panel, Figure 4) or the 1-s standard positions (lower panel, Figure 4). This demonstrates that there are qualitatively different patterns of recall in the two conditions that are perceptually challenging (5-s intersection, 1-s standard). We argue that this qualitatively different pattern of data likely reflects the presence of imagery processes on the 5-s intersection condition, but not on the 1-s (or 5-s) standard condition, at least on those conditions where the Piece effect is robust (intersection game positions).

Computer Simulation Study 2

In the simulations presented above, we assumed that, during perception, pieces within a chunk had to be re-centred individually (serially) in the mind's eye, before chunks could be recognized. This assumption was consistent with Kosslyn et al.'s findings (1988), which showed that the generation of mental images is done serially. A more lenient assumption would be that a group of pieces could be shifted in parallel. We carried out simulations to test this alternative assumption. We kept the program the same as for the main simulations but assumed that a group of pieces lying within CHREST's visual field could be shifted in parallel in 125 ms.

The results of the simulation are shown in Table 1. While the r^2 values are similar for the serial and parallel models (92% and 93% respectively, on average), the AAD values for the serial model were smaller than those observed with the parallel model (3.15 vs. 8.99 for the serial and parallel models, respectively). A similar outcome was observed with the SSE values (70.7 vs. 670.1 for the serial and parallel models, respectively). Thus, parallel shifting leads to a worse, rather than better, fit.

General Discussion

To study mental imagery and chunking, we created a new type of experimental material in which chess pieces were placed on the intersection between squares.

Predictions were made by running simulations with CHREST, a computational model of expertise. We manipulated the location of pieces (standard vs. intersection), skill, and position type. The simulations assessed the effects of these manipulations on recall. An experiment with chessplayers assessed the accuracy of CHREST's predictions.

CHREST made several predictions that related to processes putatively carried out in the mind's eye. First, CHREST predicted that intersection positions should be recalled worse than standard positions. This effect was clearly present in the human data (significant effect of Layout; Table 1). Second, within the intersection positions, CHREST predicted that the skill difference in recall should be larger with the game positions than with the randomized positions. This was observed in the human data (significant Skill by Position Type interaction; Tables 1, 2). A skill effect was only robust on the game positions, and was not observed on the randomized positions (Table 2). Third, the time parameters of CHREST were also well supported. In general, the data supported the idea that pieces must be re-centred in the mind's eye before pattern recognition can happen, and they also provided support for the assumption that the transition-time is 125 ms.

Despite these successes, data from the human experiment challenged CHREST's predictions. CHREST predicted significant skill slopes on all intersection positions, but the data revealed that a significant slope was only observed on the game positions (Table 2). It is possible that the skill effects on the randomized positions are too small to be detected reliably in our experiment (note that the slopes all had positive values with the human data, although the slope with the random positions was negligible).

The study had strengths. First, given that chess memory is a well-studied area, we used a memory task to study imagery. There was direct evidence that imagery did indeed play an important role in the memory task: We found that participants were better at recalling bishops than knights on the intersection positions, presumably because they found it easier to manipulate the bishop in the mind's eye given that the transition for the bishop (but not knight) is congruent with its typical movement. This Stroop-like interference effect parallels that reported by Bachman and Oit (1992) using a different imagery task, and provides additional evidence that imagery played an important role in task performance. The pattern of errors of commission for bishops and knights was also supportive of imagery processes along the SE-NW diagonal line (Human Study 1).

Second, we note that CHREST makes absolute predictions about performance, and that these predictions were correct in a number of cases. For example, the decrease in recalling game positions in the intersection condition as compared to the standard condition is explained by the fact that the ability to access chunks and templates, whose core consists of large chunks, is made harder. This in turn is explained by the assumption that carrying out mental transformations in the mind's eye to re-center the pieces has a time cost, specified by the base and square CHREST parameters.

Third, the seriality assumption was supported by the data (Simulation Study 2). We emphasize that CHREST had simulated a number of phenomena (e.g., recall of game and random positions or positions modified by mirror-images) several years before the current data were collected. While the model has several parameters, they are all set and thus the number of degrees of freedom of the model is small. The main degree of freedom is the type and amount of input used to let CHREST acquire chunks and templates. To our knowledge, no other theory of expertise makes predictions at this level of detail.

Last, we recruited a sample of players ranging from weak club players to grandmasters which was of sufficient size to detect the modest associations present in the data.

The study also had a number of limitations. The imagery task we used was somewhat artificial (e.g., compared to a check detection task). For example, in our task the pieces only needed to be mentally shifted half-a-square (rather than up to 7 squares), and they also only needed to be mentally shifted in the diagonal plane (and not in the horizontal/vertical place). Strictly speaking, therefore, our results only pertain to a special case of imagery that is atypical for chess players. Thus, the generalizability of the findings is not clear. Nonetheless, it is encouraging that the timing data derived from our task converge with estimates derived from different tasks. In addition, our procedures did not allow us to address fine-grained questions about the psychological processes underlying the imagery. For example, we do not know the extent to which the re-centering is conducted automatically or whether it is partly under conscious control.

In addition, the simulations were conducted in a manner as close as possible to earlier simulations. Later versions of CHREST will have to (a) better capture the detail of how the mind's eye generates and maintains visual images; and (b) model the differential recall of bishops and knights. Both these issues were outside the scope of the current paper. Later versions may also address the import of additional assumptions (e.g., the re-placement assumption in recall).

In conclusion, the simulation and human data reported in this paper have shed light on mental imagery and chunking. Perhaps the most arresting finding is that CHREST's time parameters, which were based on the sparse and somewhat inconsistent data available to De Groot and Gobet (1996), turned out to be surprisingly accurate. While previous simulations have supported CHREST's mechanisms for explaining perception and memory (e.g., De Groot & Gobet, 1996), the present paper establishes the plausibility of CHREST's mechanisms for explaining mental imagery, at least in the domain of chess.

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Footnotes

[1] Pointers might be implemented by short-term memory neurons in the prefrontal cortex firing in synchrony with neurons in posterior areas of the brain. Capacity of STM (i.e., the number of pointers that can be held simultaneously in STM) would then be a function of the number of distinct frequencies available (e.g. Ruchkin, Grafman, Cameron, & Berndt, 2003).

[2] The BCF (British Chess Federation) rating is an interval scale ranking competitive chess players, similar to the Elo rating (Elo, 1978), a more widely used rating system. Skill levels have standard names, which are used consistently in this paper (in parentheses, the approximate corresponding range in BCF points): grandmaster (GM, normally above 240), international master (IM, 225 - 240), master (200-225), expert (175-200), class A players (150-175), class B players (125-150), and so on. There is an international FIDE rating (also called Elo rating) but usually national federations have their own rating (e.g., BCF).
The formula for converting BCF into Elo is: (BCF*5)+1250. The World Chess Federation (FIDE, *Fédération Internationale des Echecs*) publishes rating lists of its members every three months and awards titles such as grandmaster.

[3] There are two ways that the knight move is typically taught, one combining horizontal and vertical movements (2 squares, 1 square; 1 square, 2 squares) and the second involving a horizontal or vertical move then a diagonal move outward (1 square, 1 square). Thus, under certain conditions, the knight could be imagined as moving diagonally. However, the diagonal movement is clearly less closely associated with the knight than with the bishop (which only moves diagonally). In addition, we suspect that adult chess players typically represent the knight's movement as a straight line between the home and target square (and not in terms of horizontal/vertical/diagonal shifts).

Table 1

Recall by Net Size/Skill and Position Type

		Standard					Intersection								
Net Size	Skill	Game	1/3	2/3	Rand.	3/3	Trans.	Game	1/3	2/3	Rand.	3/3	R^2	AAD	SSE
300k		79.5	52.8	26.2	21.7	15.2	serial	44.8	27.9	17.5	15.3	10.7	0.94	5.1	165.7
							parallel	68.9	42.2	24.1	19.8	14.2	0.95	15.5	1608.5
	GMs	**83.7**	**28.7**	**20.3**	**18.3**	**14.8**		**40.4**	**19.7**	**10.8**	**9.5**	**11.2**			
15k		62.5	36.3	19.5	16.6	11.3	serial	37.9	22.9	14.5	11.4	7.5	0.94	2.6	42.2
							parallel	54.3	31.7	18.6	15.3	10.7	0.96	8.3	549.0
	Experts	**61.3**	**25.9**	**19.1**	**17.0**	**16.3**		**36.4**	**19.6**	**10.1**	**12.2**	**10.5**			
3k		49.4	28.1	17.1	14.4	8.7	serial	30.4	19.4	12.2	9.5	5.4	0.91	2.7	44.4
							parallel	47.5	26.4	16.4	13.7	8.0	0.95	6.7	341.3
	Class A/B	**55.1**	**22.2**	**16.2**	**14.1**	**13.7**		**32.6**	**17.8**	**10.4**	**12.3**	**10.5**			
1k		37.6	24.5	15.9	13.3	7.2	serial	23.7	15.7	10.4	8.1	4.1	0.90	2.2	30.5
							parallel	33.6	23.0	15.4	12.4	6.1	0.88	5.4	182.4
	Class C/D	**40.1**	**16.9**	**15.4**	**12.3**	**12.0**		**26.3**	**15.6**	**7.4**	**9.7**	**7.7**			

Note: Mean % recall by Net Size/Skill and Position Type. Data are shown for transition-time = 125 ms. The human data, broken down by skill-level, are shown for comparison (data in bold). Key: Trans. = transition type; serial = pieces shifted in series (one-by-one) in the mind's eye, parallel = pieces shifted in parallel (as a group) in the mind's eye; AAD = average absolute deviation (the smaller, the better); SSE = sum of squared errors (the smaller, the better). GMs = Grandmasters (n = 7), Experts (n = 12), Class A/B (n = 10), Class C/D (n = 7).

Table 2

% Correct Recall: Results of Multiple Regression Analyses.

Position Type	R^2	BCF rating	Age	VM
Game	15%	0.10* (0.05)	-0.25 (0.31)	0.45 (0.34)
		0.32* (0.18)	-0.15 (0.18)	0.22 (0.17)
One-Third Randomized	25%	0.029 (0.028)	-0.38* (0.16)	0.30# (0.18)
		0.17 (0.17)	-0.40* (0.17)	0.27# (0.16)
Two-Thirds Randomized	24%	0.019 (0.018)	-0.16 (0.10)	0.26* (0.11)
		0.18 (0.17)	-0.27 (0.17)	0.37* (0.16)
Random	30%	0.001 (0.015)	-0.15# (0.09)	0.27** (0.10)
		0.01 (0.16)	-0.29# (0.16)	0.42** (0.15)
Truly Randomized	27%	0.023# (0.017)	-0.10 (0.10)	0.30** (0.11)
		0.22# (0.16)	-0.17 (0.17)	0.43** (0.15)

Note. For each position type, a regression was performed by entering BCF rating, Age, and VM in the same block as independent variables. The dependent variable was percentage recall. For each regression, the R^2, unstandardized (upper row), and standardized (lower row) parameter estimates (SE), are shown (for each predictor).

Key: VM = Visual Memory; # $p < 0.10$, * $p < .05$, ** $p < .01$. All p values for effects of BCF rating refer to one-tailed tests; other p values reflect two-tailed tests.

Table 3

% Recall of Bishops and Knights, Intersection Positions

	Bishops					Knights				
Skill	Game	1/3	2/3	Rand.	3/3	Game	1/3	2/3	Rand.	3/3
GMs	35.7 (22.9)	13.7 (9.22)	2.38 (4.30)	8.50 (6.82)	9.75 (7.62)	10.7 (8.63)	4.11 (4.06)	10.3 (4.87)	11.1 (13.4)	7.32 (4.22)
Experts	24.3 (18.6)	14.9 (12.0)	2.78 (11.1)	11.1 (6.80)	11.0 (7.96)	11.5 (11.3)	7.08 (8.55)	7.29 (7.26)	12.7 (10.7)	8.86 (7.50)
Class A/B	21.7 (14.8)	13.8 (8.57)	6.11 (6.65)	10.5 (8.11)	7.62 (9.52)	6.25 (13.5)	7.38 (7.32)	6.46 (7.99)	16.5 (13.2)	9.92 (6.97)
Class C/D	9.52 (7.50)	11.3 (11.5)	6.35 (5.00)	7.65 (9.11)	6.24 (6.36)	3.57 (6.10)	4.11 (4.06)	5.26 (9.60)	11.1 (6.59)	8.34 (7.45)
All (N = 36)	22.9 (18.3)	13.7 (10.1)	4.32 (5.16)	9.76 (7.46)	8.88 (7.97)	8.33 (10.8)	6.01 (6.69)	7.25 (7.46)	13.1 (11.2)	8.75 (6.60)

Note: Mean % recall (SD) of Bishops, Knights by Skill and Position Type. GMs = Grandmasters (n = 7), Experts (n = 12), Class A/B (n = 10), Class C/D (n = 7).

<u>Figure Captions</u>

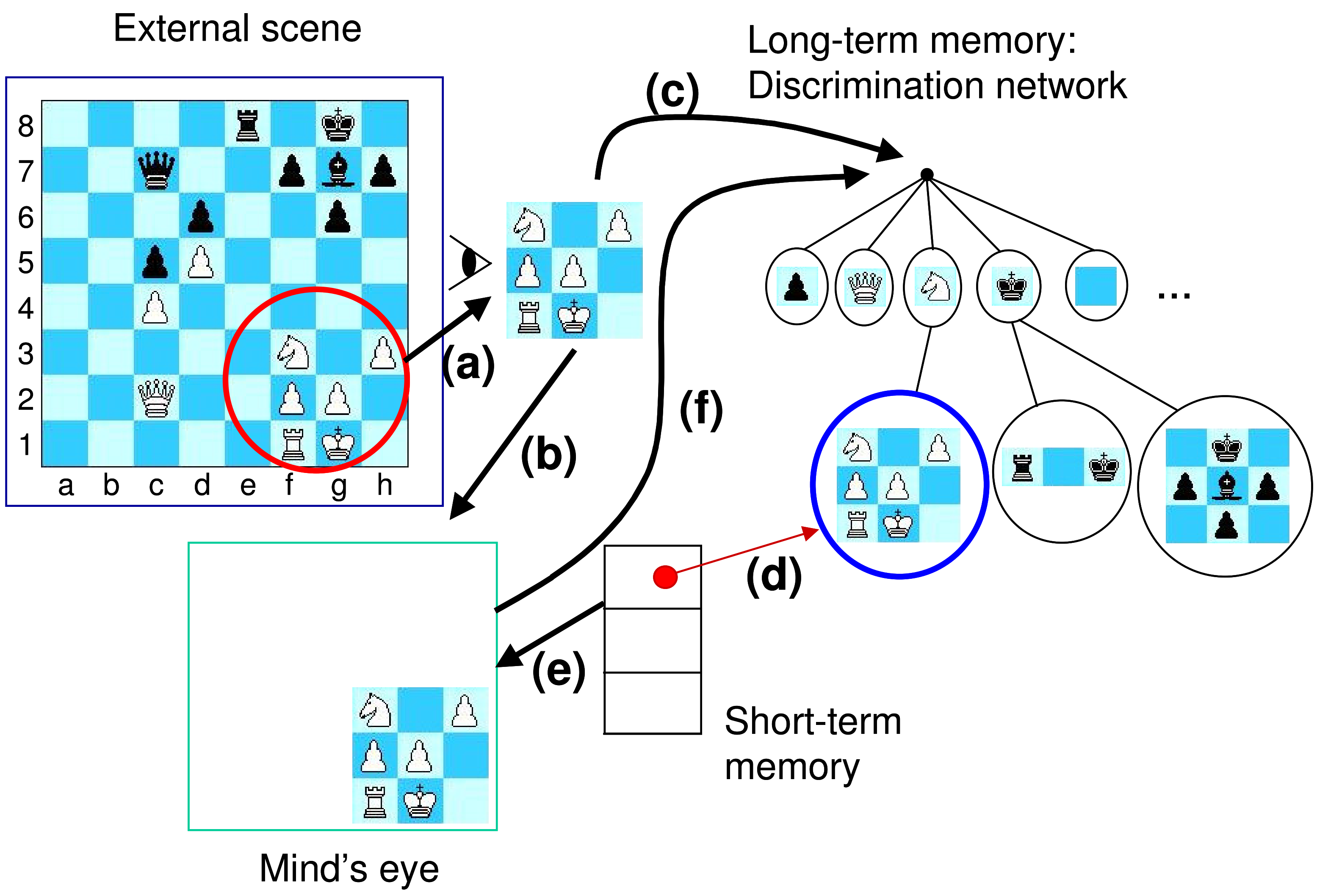
Figure 1. CHREST consists of 4 components: a simulated eye, a discrimination network giving access to LTM, a short-term memory, and a mind's eye. The simulated eye selects a portion of the external display (the "visual field"), shown by (a) in the Figure 1. This information is sent both to the mind's eye (b) and LTM (c). If the information is recognized in LTM by accessing a node (i.e., a chunk), a pointer to this chunk is put in STM (d), and the information is unpacked in the mind's eye (e). In turn, the information in the mind's eye can be used to access a node in LTM (f). Note that LTM chunks encode information about location (e.g., the two white pieces on the 1st row would be encoded as Rook on f1 and King on g1.

Figure 2. Processes involved in shifting pieces in the mind's eye in CHREST (see text for details). The circle in the top diagram reminds the reader that the diagram is within the current visual field, and the coordinates that chunks encode information about location.

Figure 3a. Examples of the 5 position types used in the experiment (Intersection positions).

Figure 3b. Recall requirements for standard (top) and intersection (bottom) positions. On intersection positions, participants were required to place pieces on the intersections of squares.

Figure 4. Recall of Bishop vs. Knight as a function of the type of position (game and random) and type of experiment (standard layout, 5 s; intersection layout, 5 s; and standard layout, 1 s).


External scene
8
7
6
5
4
3
2
1
a b c d e f g h
(a)
(b)
(c)
Long-term memory:
Discrimination network
(f)
(d)
(e)
…
Short-term
memory
Mind's eye

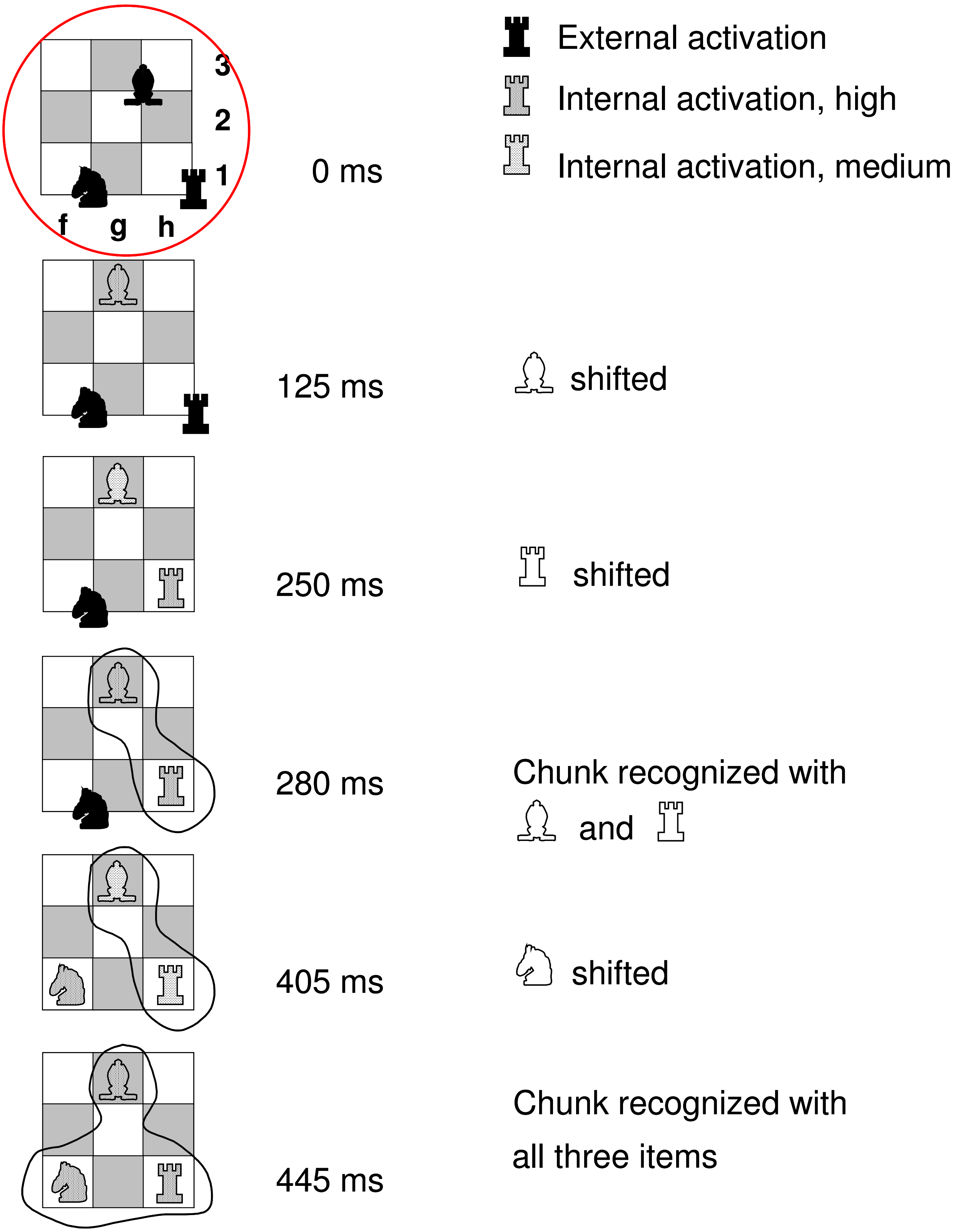

3
2
1
f
g
h
0 ms
External activation
Internal activation, high
Internal activation, medium
125 ms
shifted
250 ms
shifted
280 ms
Chunk recognized with
and
405 ms
shifted
445 ms
Chunk recognized with
all three items

Figure 2

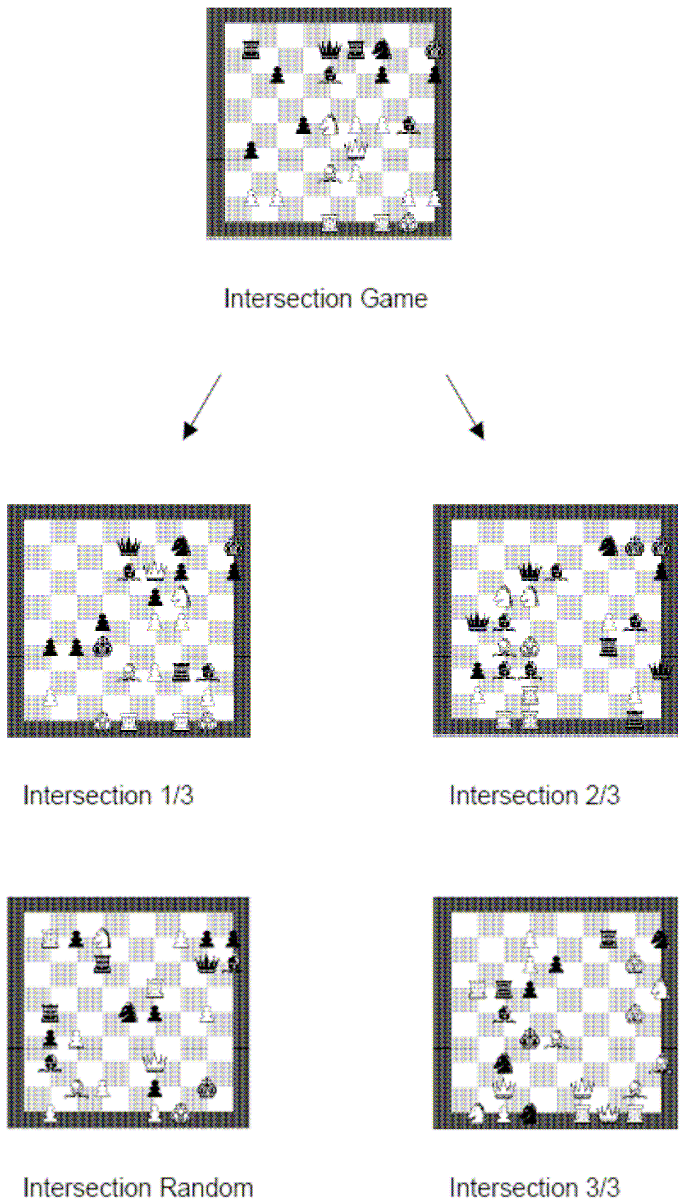
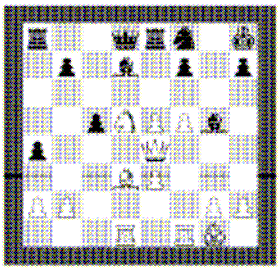
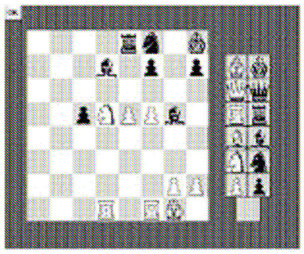

Intersection Game
Intersection 1/3
Intersection 2/3
Intersection Random
Intersection 3/3

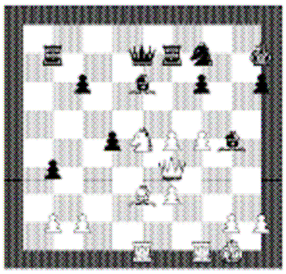
Figure 3a



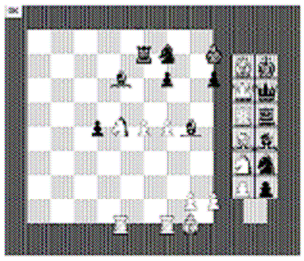
Standard Game



Recall on **Standard** positions: Participants place pieces on centers of squares



Intersection Game



Recall on **Intersection** positions: Participants place pieces on intersections

Figure 3b

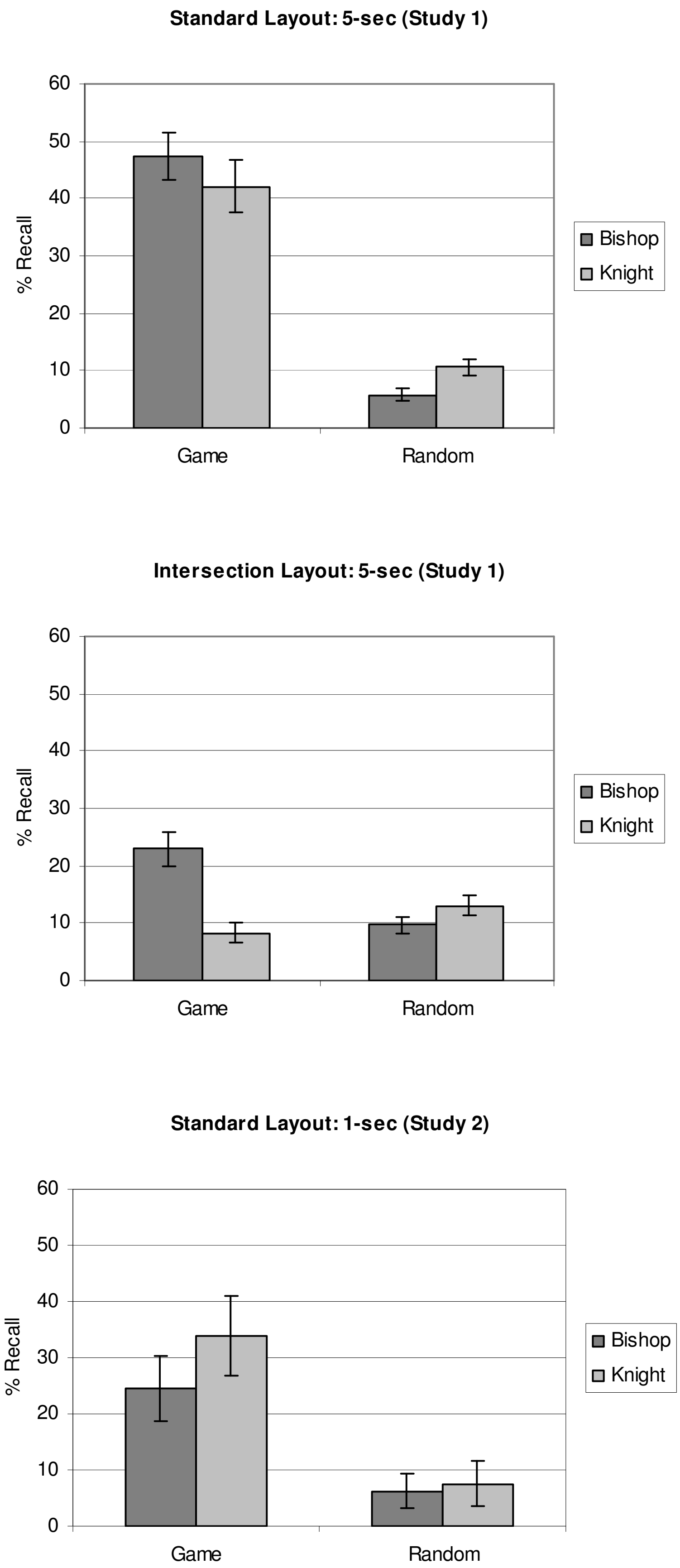

Standard Layout: 5-sec (Study 1)
% Recall
60
50
40
30
20
10
0
Game
Random
Bishop
Knight
Intersection Layout: 5-sec (Study 1)
% Recall
60
50
40
30
20
10
0
Game
Random
Bishop
Knight
Standard Layout: 1-sec (Study 2)
% Recall
60
50
40
30
20
10
0
Game
Random
Bishop
Knight

Figure 4