INFORMATION-PROCESSING ANALYSIS OF PERCEPTUAL PROCESSES IN PROBLEM SOLVING [1]

HERBERT A. SIMON [2] AND MICHAEL BARENFELD

Graduate School of Industrial Administration, Carnegie-Mellon University

A theory is proposed to explain, in information-processing terms, some common phenomena in the initial perceptual phases of problem solving, to show that some existing computer programs for heuristic search and learning already contain basic processes that will produce these phenomena, and to show how simple organizations of the processes enable the programs to parallel human behavior. The theory is particularized in a computer program to simulate the eye movements, during the first 5 seconds, of subjects choosing a move in chess. The application of the theory is illustrated by an example, and its consistency is shown with data on memory of chess positions and with existing knowledge of short-term memory parameters.

Information-processing theories of human problem solving, particularly those employing computer simulation as their means of formalization and analysis, have emphasized the problem solver's selective search through the "tree" of solution possibilities. Both the authors of these theories and their critics agree that heuristic search, while a prominent feature of problem-solving behavior, is by no means the whole of it—and perhaps not even the most crucial part. In particular, theories that describe problem solving only as search fail to capture and explain processes that are especially visible during the first 5 or 10 seconds after a problem situation is encountered.

There is evidence—some of which will be mentioned—that a great deal of structure may be imposed on the problem situation by subjects in problem-solving experiments during those first seconds of exposure. Some critics of information-processing theories have argued that this initial structuring activity, which they usually describe as "perceptual" rather than "cognitive," constitutes the really "significant" part of the problem-solving process, the subsequent heuristic search being relatively "routine." These

critics have sometimes concluded that the initial perceptual processing would require information-processing systems fundamentally different from those that have been postulated to explain heuristic search behavior (Tichomirov & Poznyanskaya, 1966).

Evidence for the existence and character of the initial perceptual activities comes largely from situations where problems are presented to subjects in visual form. The evidence takes at least two forms: (*a*) records of subjects' eye movements during the first few seconds after problems are presented to them, and (*b*) tests of subjects' abilities to retain information from complex visual displays after a few seconds' exposure.

It is the purpose of this paper to propose an explanation in information-processing terms of the initial perceptual phases of problem solving, to show that some existing computer simulation programs for heuristic search and learning already contain the basic processes required for such perceptual activities, and to show how simple organizations of these basic processes enable the programs to parallel the behavior of human subjects.

Since the most extensive research on perception in problem solving deals with the perception of chess positions, the present analysis is made in terms of this task. The authors' aim is to describe a computer program that can explain, in information-processing terms, the known empirical phenomena (*a*) relating to eye movements during

initial view of a chess position, and (b) relating to subjects' retention of information about a chess position after a few seconds' exposure to it. The emphasis will be on describing the theory. This paper is not an attempt to review the considerable literature on eye movements and perception in chess; nor, except by way of illustration, will detailed comparisons of specific simulations with specific data be made. Instead, the authors state the central theoretical issues and propose a solution to them.[3]

PERCEPTION IN CHESS

Existing computer chess-playing programs, like most other problem-solving programs, are based largely on the technique of selective heuristic search through the tree of legal continuations from the given game position. However, during the first moments—for example, 15 seconds more or less—during which he is exposed to a new position, a skilled human player does not appear to engage in a search of move sequences. Instead, he appears to be occupied with perceiving the essential properties of the position, which will suggest possible moves to him and help him to anticipate their consequences. He appears to be gathering information about the problem, rather than seeking an actual solution. In summing up his extensive empirical studies of the thought processes of chess players, de Groot (1965, p. 396), observes:

From the analysis of protocols and from the additional experiments on chess perception we have learned that this is a first Phase of problem formation.

The process in the first Phase is characterized by a perceptive and receptive, rather than actively organizing, attitude on the part of the subject . . . .

Subsequent research by de Groot (1966) and his students (e.g., Jongman, 1968), provides additional support for this conclusion.

Superficially, it would appear that existing computer chess programs do not provide an explanation of these human behaviors— hence, they have questionable status as theories of human problem solving in chess. To be sure, if one makes a detailed examination of what is going on in the computer programs that play chess by selective search, one finds that they too contain processes that would be labeled "perceptual." If they did not, the programs could not search selectively. Consider, for example, MATER, a program that searches for checkmating combinations (Baylor, 1965; Baylor & Simon, 1966). Among the subroutines it contains—which are employed in the service of higher level routines for generating and testing moves—is one that finds the direction between two given squares (notices, e.g., whether they lie on the same file); a second determines whether there is a piece on the rank, file, or diagonal between two given squares; another, whether a specified piece is under attack; another, whether a given square is under attack; another, whether a given square is defended; and so on (Baylor & Simon, 1966, p. 446).

EYE MOVEMENTS

While de Groot provided convincing evidence that his human subjects, during the first 5 or 10 seconds of looking at a position, were more concerned with extracting information about the position than with exploring sequences of moves, his experimental techniques (relying primarily on thinking-aloud protocols) did not permit him to establish the precise sequences of processing activities during this period. In order to obtain additional information about "noticing" behaviors during initial exposure of subjects to positions, Tichomirov and Poznyanskaya (1966), and subsequently, other researchers (de Groot, 1966; Winikoff, 1967),

[3] Jongman (1968) has also sketched out, but not programmed, a process model to explain the perceptual phenomena. Jongman's dissertation was not available to the authors when the program described here was constructed, but some of the data gathered by de Groot, Jongman, and Noordzij in the Amsterdam project, including the data reported in de Groot (1966), and the project's eye movement films were accessible. Jongman's model, the details of which can be found in his thesis, especially page 142, focuses primarily on the determination of the initial features to be noticed rather than the subsequent eye movements, thus is complementary to the program described here, filling out some of the aspects that have been handled sketchily. The authors are grateful to their Amsterdam colleagues for collaboration and exchange of ideas on this subject that extends over a decade.

have recorded eye movements with sufficient accuracy to determine the location of each fixation within one or two squares of the chess board.

Both the problems of calibrating the instruments and the nature of the human visual apparatus make it impossible to establish with assurance the precise square to which a subject is attending at any given moment. A single fixation may—and probably does—enable him to discover what pieces are standing on several neighboring squares. Peripheral vision permits some information to be gathered about the status of even more distant squares. Indeed, such peripheral information is necessary to direct the eyes to new fixation points if the eye movements are to be other than random. Records of eye movements can only show the succession of fixations; they cannot show precisely what information is being processed at each moment.

The eye-movement records gathered by Tichomirov and Poznyanskaya, as well as some gathered by Winikoff (1967, Ch. 6 and 7), and others by de Groot's students in Amsterdam (personal communications), show rather consistently that the fixations of subjects move from one square of the board to another at a maximum rate of about four fixations per second. It appears that at each point of fixation the subject is acquiring information about the location of pieces at or near the point of fixation, together with information about pieces in peripheral vision (within, e.g., 7° of arc) that bear a significant chess relation ("attack," "defend," "block," "shield") to the piece at the fixation point.

PERCEIVER Program

To elucidate this hypothesis about the eye movements, and its implications, the authors have organized the "perceptual" processes, already contained in MATER into a new chess-perception program, PERCEIVER, that can simulate the initial sequences of the eye movements of human subjects. This paper describes PERCEIVER, then illustrates its behavior by comparing, for the same chess position, its initial simulated eye movements with an example of human data published by Tichomirov and Poznyanskaya (1966).[4] It should be emphasized that PERCEIVER is organized from processes that are present in the MATER program. (The processes are described in detail in Baylor, 1965; Baylor & Simon, 1966.)

Carrying out the simulation requires a stronger assumption than simply that the human subjects are "perceiving" the relations among the pieces on the board. It is necessary, in addition, to posit processes that will generate these perceptions in some particular sequence. The two basic assumptions incorporated in the program are:

1. The information being gathered during the perceptual phase is information about relations between pieces—usually pairs of pieces—or between pieces and squares. When the eyes are fixated on a particular piece, it is possible to detect neighboring pieces (a) that defend the piece in question, (b) that attack it, (c) that are defended by it, and (d) that are attacked by it. (Other meaningful relations could be added to this list, but the experiment was limited to these four.)

2. When attention is fixed on piece A, and one of the four relations mentioned above is noticed, connecting A with another piece, B, attention may return to A without change in fixation. If it does not, B will be fixated next.

These two assumptions are, of course, not sufficient to determine all details of the program. By changing the order in which the various items are noticed, different sequences of eye movements can be produced in the same position. It is necessary also to specify an initial point of fixation (in the simula-

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[4] Comparisons are limited to the Tichomirov-Poznyanskaya data because (a) they are the only chess eye-movement data actually published to date, (b) they explicitly interpret their data as refuting computer-simulation models of problem solving, and (c) the other (unpublished) eye-movement data known to us were obtained either from weak players or players under instructions to "remember the position" rather than "select a move." The unpublished data gathered by Winikoff and by the Amsterdam group do not contradict any of the conclusions the present authors draw from the Russian data.
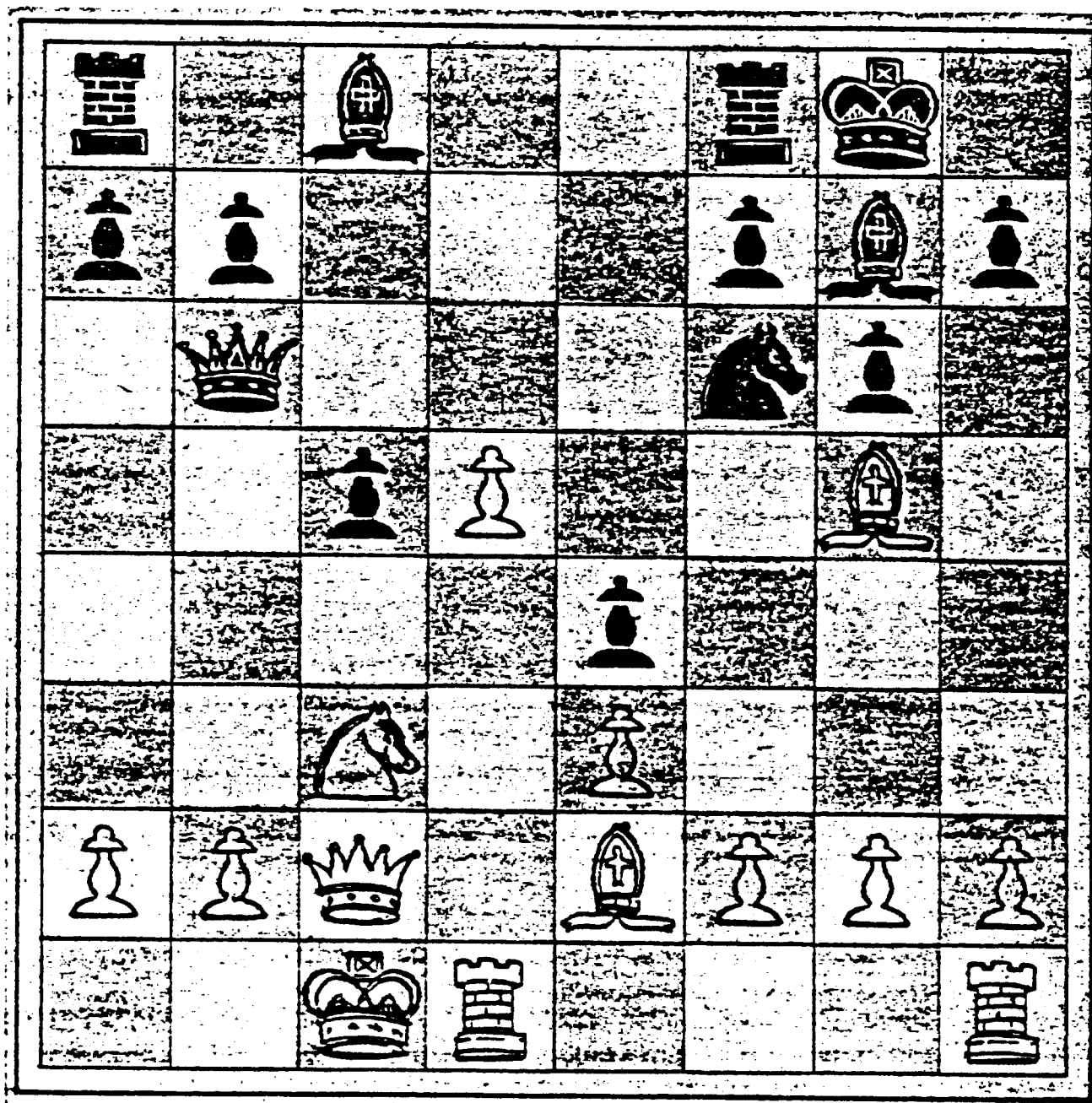
FIG. 1.   Middle game position used by Tichomirov and Poznyanskaya (1966)
(Black to play).

tion to be described, this is always a piece near the center of the board, but see Jongman, 1968, pp. 131–137). Finally, the program may be made to behave in various ways when it repeats the same cycle of fixations—it can be made more or less repetitive and stereotyped in its behavior. For the comparisons to be made here, the behavior of the program is not especially sensitive to such variations in the detail of its structure.

*Illustrative Comparison with
Eye-Movement Data*

Figure 1 shows the chess position used by Tichomirov and Poznyanskaya (1966, p. 5) in one of their experiments. Figure 2 shows the sequence of 20 fixations observed in a player of expert (just below master) caliber during his first 5 seconds of looking at this position. Figure 3 shows the sequence of 15 simulated fixations produced by the PERCEIVER program before it began recycling and halted this phase of its exploration. On Figures 2 and 3, the 10 squares are shaded on which stand the pieces whose positions would be regarded by any good chess player as critical to understanding the structure of the position. These are the pieces under attack (the two center pawns, Black's Knight, White's pawn on QN2), together with their attackers and defenders, and the two Kings.

It is obvious that both the human expert (Figure 2) and the PERCEIVER program (Figure 3) were mainly occupied with relations connected directly or indirectly with the Black pawn on White's K4, the Knight on B6, and the White pawn on QN2. By the construction of the program, all of PERCEIVER's fixations fell on squares occupied by pieces. Either for reasons of calibration, or from other causes, six of the human player's fixations fell on unoccupied squares. Nevertheless, the figures exhibit considerable concordance between the objects of attention in the two cases; and the eye-movement fixations, actual and simulated, reveal almost complete preoccupation with the 10 critical pieces.

The trace printed by the PERCEIVER program shows the course of exploration over the board (Table 1). On the left are shown the 15 successive points of fixation of the program. For each fixation, on the right are listed the relations with other pieces that were noticed (centrally or peripherally) during the fixation.

The sequence can be divided into three main phases. The first five fixations relate directly to the Black pawn on White's K4, the Knight and Queen that attack it, the Knight that defends it, and the White pawn
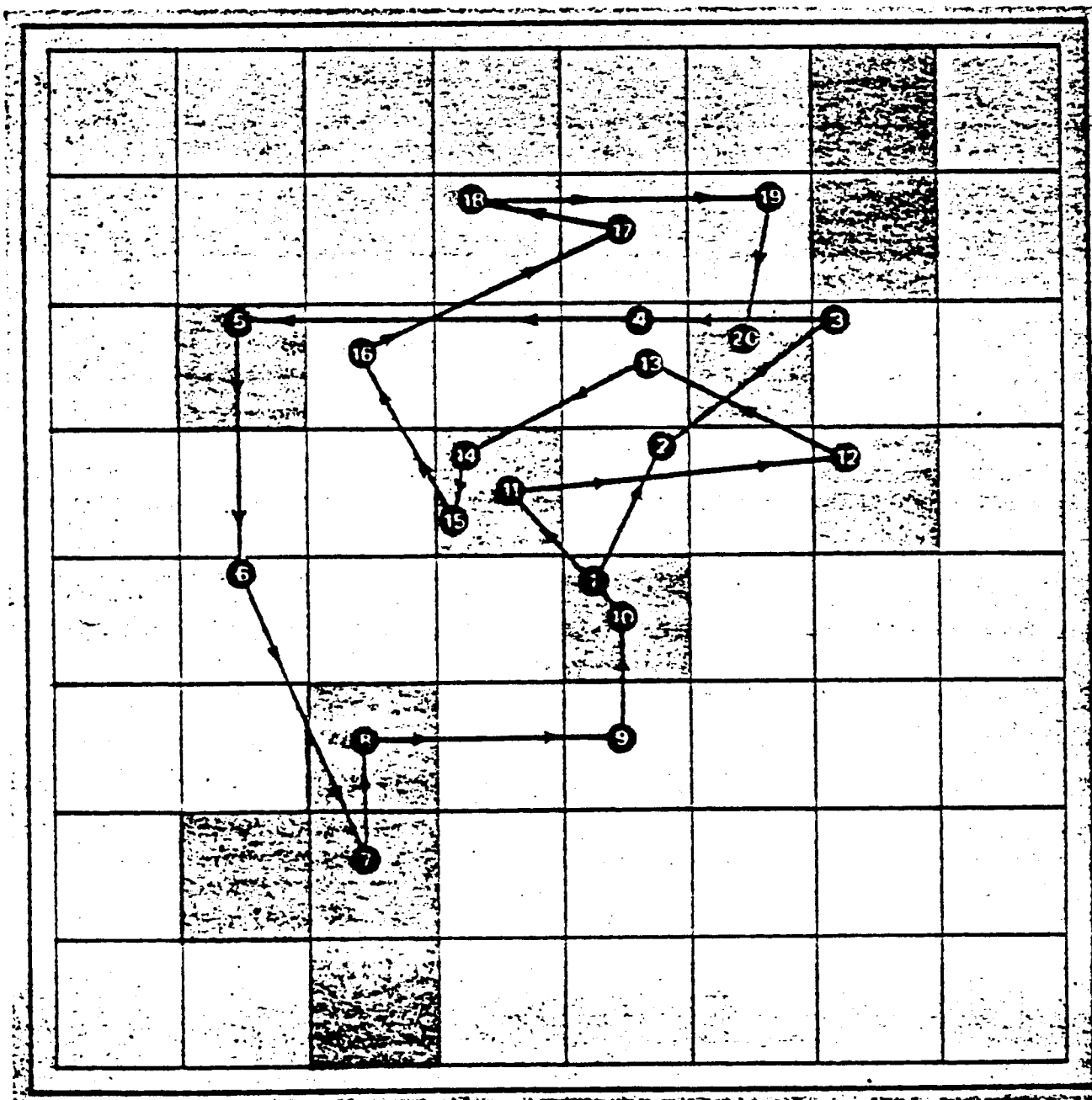

FIG. 2. Record of eye movements for the first 5 seconds (expert player, from Tichomirov & Poznyanskaya (1966)). (The 10 squares occupied by the most active pieces (see Figure 1) are shaded.)
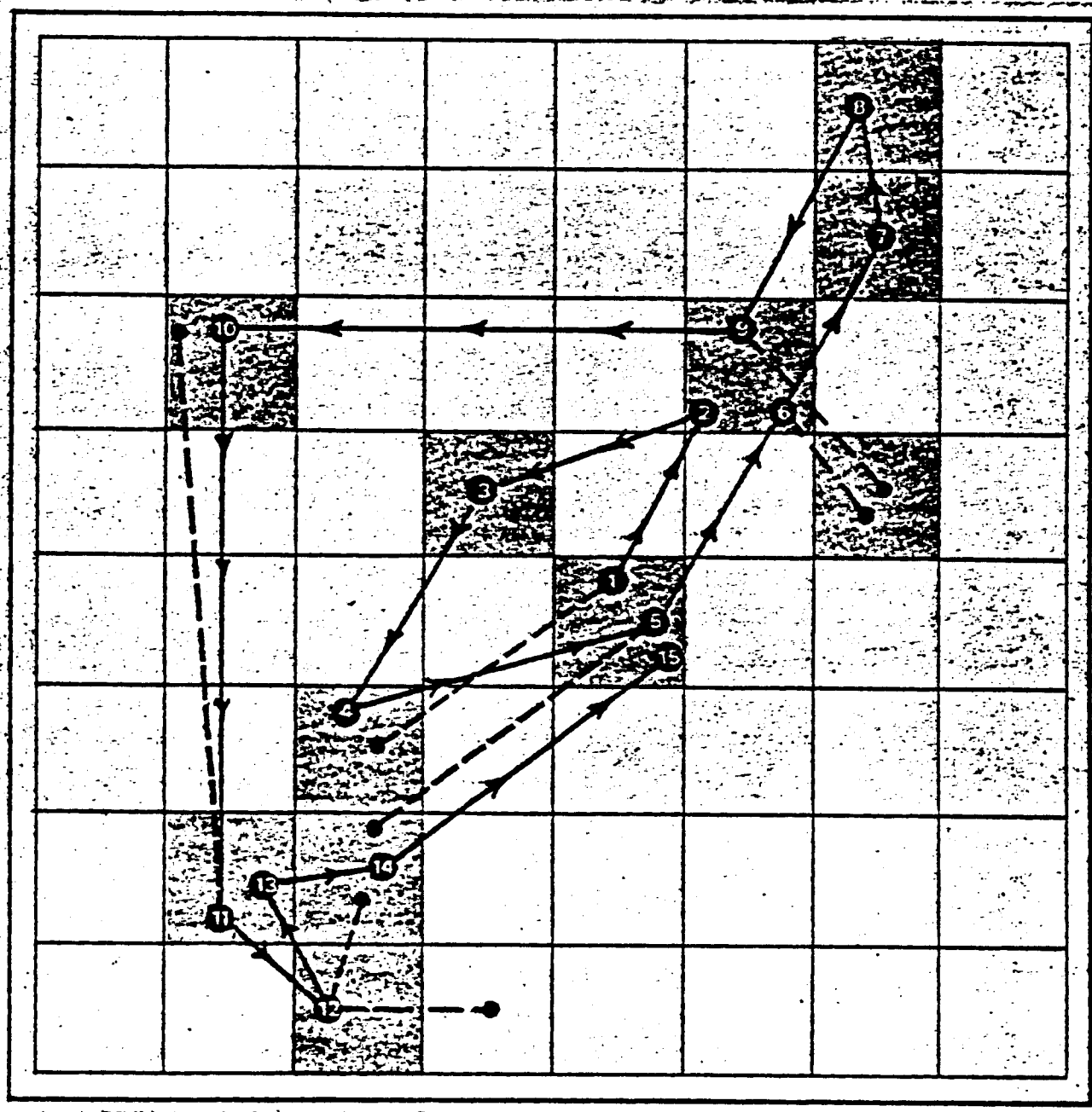
FIG. 3.   Record of simulated eye movements during period of initial orientation—PERCEIVER program. (Solid line—eye movements; broken lines—relations noticed peripherally. The 10 squares occupied by the most active pieces (see Figure 1) are shaded.)

on Q5 that the same Knights attack and defend. The next four fixations concern the Black Knight, the Bishops that attack and defend it, respectively, and its other relations with Black's castled King's position. The defense of the Knight by the Black Queen shifts attention to the Queen, then to the White Knight's pawn she attacks. The next four fixations have to do with that pawn and its defense. The final two fixations return, via the White Queen, to Black's King's pawn.

Note that the Black Queen links the two main arenas—the one around the Black pawn on K4 and Knight on B6, and the one around

the White pawn on QN2. The two situations are also linked by the White Queen, which appears in the first, third, and last episodes of the sequence. The Tichomirov-Poznyanskaya sequence reveals the same two foci of attention (though with less emphasis on the situation around QN2), and the same dual relations of the Queens connecting them.

PERCEIVER's focus of attention on these particular relations does not rest on subtle or complex evaluations of what is "important" on the board. If attention follows a train of associations in such a web of relations, it will simply be brought back re-

peatedly to the points in the web where the density of relations is highest.

In the position shown in Figure 3, the sequence of fixations identifies the Black pawn on K4 as underdefended—attacked by Knight and Queen, but defended only by a Knight. At the end of the initial perceptual phase, PERCEIVER undertakes a new exploration to find moves that would protect the pawn. The same perceptual processes are used as before, but in a slightly more complex way. Working from the pawn that is under attack, and following the ranks, files, and diagonals that converge on it, PERCEIVER discovers squares from which a piece of an appropriate kind can defend the pawn, then searches for a piece that can be brought to the square. Thus, following the King's file to K8, PERCEIVER finds a square from which a Rook or Queen could defend the pawn, then discovers the Rook on B8 which can move to that square. In this way (Figure 4), PERCEIVER discovers the Rook move, the move of the Bishop from QB8 to KB5, and two Queen moves that will protect the pawn. The eye movements of the human expert show the Rook move being discovered in the same way —fixations begin at the pawn, move up the file to K8, then over to the Rook (Tichomirov & Poznyanskaya, 1966, p. 6, Figure 2).

REPRODUCTIONS OF POSITIONS FROM MEMORY

The example shows that a very simple program, using perceptual processes of the kinds already employed in computer chess programs, moves its attention about the board in a way that resembles the eye movements of a human subject. Since the central concerns are theoretical, a more extensive comparison of the program's behavior with eye-movement data will not be undertaken. The authors simply assert that there is nothing particularly "atypical" about the position used for illustration, and that the program will behave in a similar manner when faced with other board positions from chess games.

The broader question is whether the information that can be extracted from the position by these perceptual processes is adequate

TABLE 1

SEQUENCE OF FIXATIONS AND NOTICING ACTS: PERCEIVER PROGRAM

1. Black pawn (K4)	attacked by defended by	White Knight Black Knight
2. Black Knight	attacks	White pawn (Q5)
3. White pawn (Q5)	defended by	White Knight
4. White Knight	attacks	Black pawn (K4)
5. Black pawn (K4)	attacked by defended by	White Queen Black Knight
6. Black Knight	attacked by defended by	White Bishop Black Bishop
7. Black Bishop	defended by	Black King
8. Black King	defended by	Black Knight
9. Black Knight	attacked by defended by	White Bishop Black Queen
10. Black Queen	attacks	White pawn (N2)
11. White pawn (N2)	defended by	White King
12. White King	defended by defended by defends	White Rook White Queen White pawn (N2)
13. White pawn (N2)	attacked by defended by	Black Queen White Queen
14. White Queen	attacks	Black pawn (K4)
15. Black pawn (K4)		

to account for the known ability of chess masters to reproduce chess positions after brief exposure (5 or 10 seconds) to sight of the board. Notice that there are two parts to the human performance: (a) extracting from the chessboard the totality of information about the chess position, and (b) retaining all of this information long enough to reproduce the position from memory. The PERCEIVER program is concerned principally with the extraction of information from the board. To deal with the retention, another component of the information-processing theory of cognition must be referred to—the EPAM (Elementary Perceiver and Memorizer) theory of rote learning (Gregg & Simon, 1967). EPAM simulates the
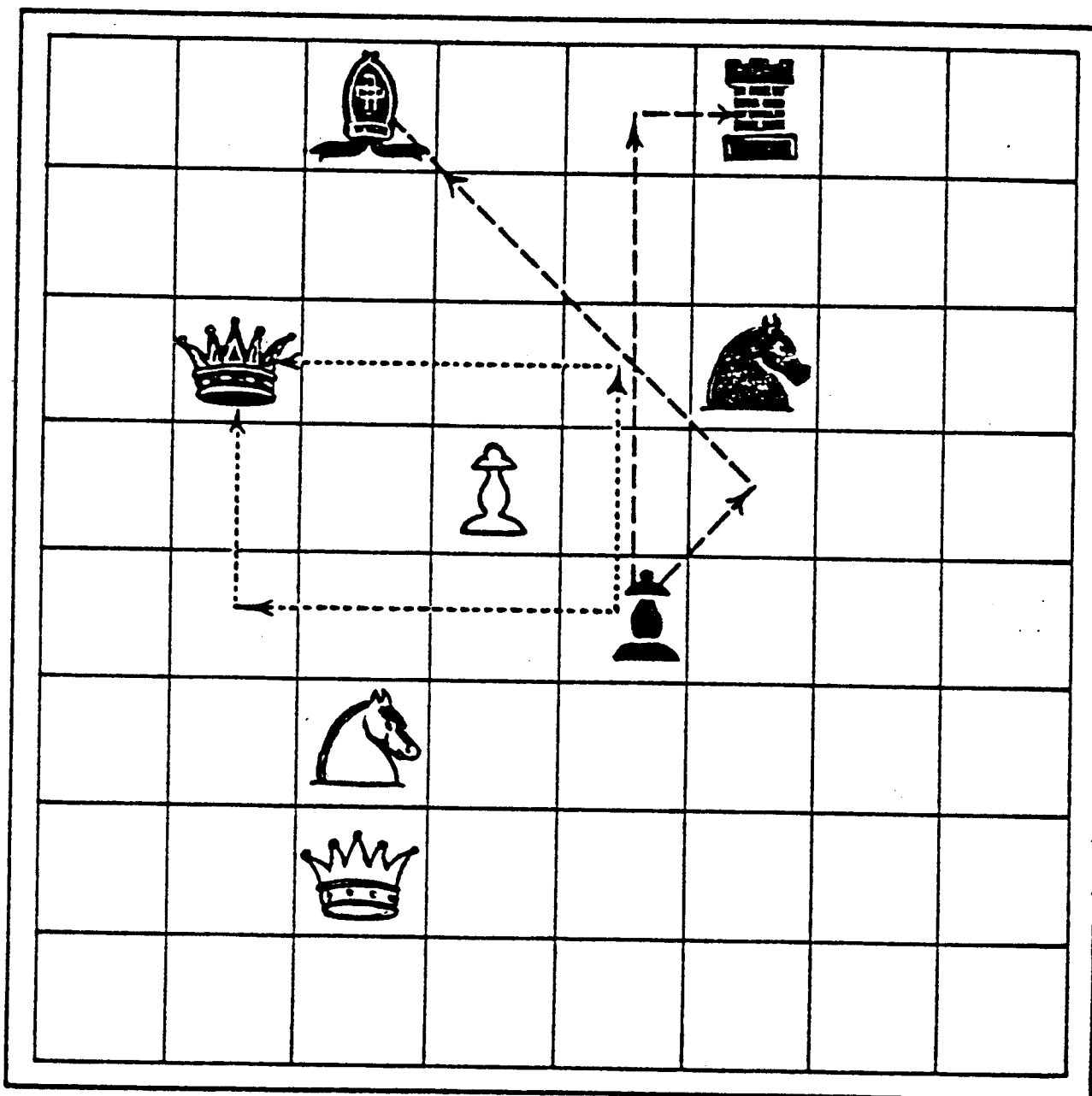
FIG. 4.   Record of simulated eye movements subsequent to orientation period—
PERCEIVER program.

recognition and fixation processes in learning at a finer level of detail than do the programs that simulate problem solving, hence it is more relevant than they to questions of short-term memory.

Experimental Results

In a series of striking experiments, it has been shown that the ability of a subject to reproduce a chess position after a few seconds' exposure to it depends sensitively on (a) the subject's chess proficiency and (b) the "meaningfulness" of the position (de Groot, 1965, pp. 321–334; de Groot, 1966, pp. 35–48; Jongman, 1968, pp. 35–43). "Meaningfulness" can be manipulated by contrasting the reproduction of positions from actual games (but games not known to the subjects) with the reproduction of boards having the same pieces as the game positions, but placed at random.

In summary, de Groot and Jongman report that (a) after 5 seconds' sight of the board, a grand master or a master can reproduce a chess position almost without error; (b) the weaker the player below this level, the more errors he makes in the reproduction—very weak players can place only half a dozen pieces correctly; and (c) with random boards, the performances of grand masters and masters sink to the level of weak players, while the weak players perform as well (or as poorly) with random boards as with boards from game positions.

An explanation of chess perception must be consistent with these data if it is to be regarded as satisfactory. At the same time, the explanation must also be compatible with what is known about short-term and long-term memory. It is rather well established that (a) "seven plus-or-minus two" *chunks* can be held in short-term memory; (b) probably not more than one chunk can be transferred from short-term to long-term memory in as short a time as 5 seconds. A chunk here means any configuration that is familiar to the subject and can be recognized by him. (For a discussion of these facts, together with references, see Gregg & Simon, 1967.)

If these two facts are accepted, then the information that allows a subject to reproduce a chess position after only 5 seconds' exposure must be mainly in short-term memory; and if the position is reproduced perfectly, or nearly perfectly, it must somehow be encoded as not more than, say, nine chunks of information.

Proposed Explanation

The PERCEIVER program, taken by itself, does not satisfy these requirements. To describe a chessboard, containing 28 pieces, with the relations of "attack," "defend," and so on, would require an initial location plus at least 27 relations—even if the direction between the pieces were encoded as part of the relation. For this information to be retained in short-term memory, it must be recodable into familiar chunks, each containing, on average, three or four relations.

The mechanisms employed in the EPAM (Gregg & Simon, 1967), theory of discrimination constitute a theory of how such an encoding can be accomplished. Stimuli presented to EPAM are sorted through a discrimination net on the basis of perceivable characteristics. Stimuli, or portions of stimuli that are found to match in their characteristics with stimuli stored previously in the memory are "recognized," and are replaced in short-term memory by a single chunk that designates them. Thus, if a configuration of relations in a stimulus is recognized as familiar, the whole configuration, consisting of as many parts as there are perceived relations, can be represented in memory by a single chunk. Hence, the short-term memory, limited to holding a specified maximum number of chunks, can retain many more relations if they occur in familiar configurations than if they must be held independently in memory.

The EPAM theory of discrimination has been shown (Gregg & Simon, 1967) to make correct predictions on the effects of familiarity in rote verbal learning, hence provides an "in-principle" explanation of the chessboard reproduction phenomena. According to this explanation, clusters of related pieces in a position are recognized by chess masters as familiar constellations; hence each cluster is stored as a single chunk; less skilled players have to describe the board in a larger number of simpler chunks—hence cannot hold all the information required to reproduce the board in short-term memory. Moreover, when the same number of pieces is arranged on the board at random, few of the resulting configurations are familiar even to grand masters. Hence, they then need more chunks to describe the position than can be held simultaneously in short-term memory, and hence perform as poorly as weaker players.

Several considerations support the plausibility of this explanation of the experimental data.[5] First, the quantities involved are of the right order of magnitude. Mastership in chess requires at least several years of serious occupation with the game. In that time, a player might be expected to acquire a "vocabulary" of familiar subpatterns comparable to the visual word recognition vocabularies of persons learning to read English, or the Kanji (or Kanji-pair) recognition vocabulary of persons learning to read Chinese or Japanese. But these vocabularies are of the order of 10^4–10^5 "words" in size. Hence, sequences of seven such subpatterns

[5] The analysis of Jongman, not available when the following paragraphs were written, again provides strong direct empirical support for these hypotheses about encoding, and especially the stereotyped nature of the patterns for the castled Kings (see Jongman, 1968, pp. 83–112).

could be used to encode 10^{28}–10^{35} (i.e., $(10^4)^7$ or $(10^5)^7$) different total board positions.[6] The number of chess positions that could arise from sequences of "reasonable" moves has been estimated to lie in the range 10^{10} to 10^{15} (see Jongman, 1968, p. 33), hence well within the estimated vocabulary limits. A vocabulary of the postulated size is sufficient to supply distinct seven-chunk names to distinct chess positions.

Second, everyday chess experience, supported by de Groot's laboratory data (e.g., de Groot, 1965, pp. 324–334), suggests that the familiar chunks are configurations of several to a half-dozen pieces. But seven configurations averaging three or four pieces each can describe a board on which there are 20–30 pieces. Further, the number of different three-to-four-piece configurations that have to be posited is again consistent with the estimate of 10^4–10^5 given above. The Tichomirov-Poznyanskaya position can be used to illustrate these points—not to "prove" them, for the present authors will make free use of chess knowledge gleaned from experience and the literature. The following are configurations that would likely be familiar to a chess master (cf. Figure 1):

1. The two center pawns, the two Knights and Queen attacking and defending them, and the blocking White pawn on K3 (6 men).

2. Black's Knight, the Bishop attacking it, and Queen and Bishop defending it, and the two center pawns on which it bears (6 men).

3. White's Queen's Knight's pawn, the Queen attacking it, the King and Queen defending it, and the Knight it defends (5 men).

4. White's castled position on the Queen's side: 2 pawns, King, and Rook (4 men).

5. White's Bishop on King 2 (1 man).

6. White's King's side: Rook and 3 pawns (4 men).

7. Black's castled position: King, Rook, Bishop, Knight, and 3 pawns (7 men).

8. Black's Queen's side: Rook, Bishop, and 3 pawns (including the typically advanced Bishop's pawn) (5 men).

The authors do not assert that every chess master will break up the position into exactly the same configurations, but those listed above have been seen by any master many times. The first three chunks correspond essentially, to the three episodes in the PERCEIVER sequence. Each focuses on a critical man and its relations. Of the remainder, four describe the relatively stereotyped configurations in the four corners of the board, which would have to be picked up by PERCEIVER peripherally. The most complex is the seventh, describing the situation of Black's castled King. Yet this identical pattern for Black arises in 5–10% of all chess games between masters—the percentage varying from one era to another. (Seven configurations account for about half of the castled positions in master games.)

Notice that there is redundancy in the description—many pieces enter into more than one configuration. De Groot (1965, pp. 321–322) observes that this redundancy contributes to error correction, and that in the absence of redundant relations, isolated pieces (like the White King's Bishop) are the most easily omitted in reproduction (see also Jongman, 1968, pp. 92–93).

Obviously, there are different ways in which the relations on the board could be organized into familiar chunks. The purpose here is simply to show that the information known to be extracted by masters and grand masters in their first perception of chess positions is consistent, in quantity and quality, with a hypothesized mechanism that (a) notices relations, in the manner of PERCEIVER, then (b) recognizes and chunks configurations of such relations, in the manner of earlier programs for simulating human memory processes, such as EPAM (see Gregg & Simon, 1967). No significant new mechanisms have to be postulated to account for these data on chess perception.

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[6] A more conservative estimate would take account of the fact, to be mentioned presently, that the configurations in the corners of the board are highly stereotyped, hence perhaps only about 10^2 in number. The number of different positions made up of four such subpatterns and three other, less stereotyped, subpatterns describing the center of the board would then be about $(10^2)^4 \cdot (10^5)^3 = 10^{23}$, which still provides sufficient variety.

CONCLUSION

In this paper the authors have offered a theoretical account of the information processing that occurs in human problem solving during the initial attack on the problem, prior to the beginning of heuristic search. It was shown how perceptual processes employed in earlier problem solvers can be organized to make initial analysis of problem structure, using previous experience stored in memory to reorganize and recode a complex stimulus into a smaller number of familiar chunks.

The theoretical explanation was made more concrete by developing it for a specific task environment: chess playing. A PERCEIVER program was constructed to extract information from a chess board, and the way the program behaves in comparison with a record of human eye movements was illustrated. The authors have shown how this program, combined with EPAM-like recoding mechanisms, can account for the ability of chess masters to reproduce chess boards after brief exposure. The processes used by PERCEIVER are very similar, also, to the processes postulated recently by Simon (1967) to account for such well-known perceptual phenomena as the reversibility of the Necker Cube and the perception of "impossible" figures.

The significance of these results does not lie in the detail of the processes, which will surely need revision as knowledge grows, but in the demonstration for both of these realms that essentially the same elementary processes that have been employed to simulate problem solving and learning, operating in essentially the same kind of serial information-processing system, produce the main known features of the human perceptual performances. In these task domains, no radically different principles would appear to govern perceptual processing from those governing other central processing.

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