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The Interaction between Perceptual and Cognitive Processes in a Distributed Problem Solving Task

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ABSTRACT

This paper examines the interaction between internal and external information and the interplay between perceptual and cognitive processes in the Tic-Tac-Toe and its isomorphs. The experimental results show that different distributed representations can elicit different situational strategies, which are the determining factor affecting problem solving behavior. Planning has little effect in these tasks. The difference between perceptual and cognitive processes and that between parallel and sequential perceptual processes also affect problem solving behavior in a significant way.

INTRODUCTION

Many cognitive tasks in real world situations involve continuous interactions with an information rich environment filled with natural and artificial objects extended across space and time. These tasks all require the interwoven processing of information distributed across the internal mind and the external environment. Though few would deny that external information, in addition to internal information, is essential for these tasks, different approaches usually have different assumptions on (a) what external information is processed, (b) how external information is processed, (c) what roles external information plays, and (d) how external information and internal information are integrated during processing.

The traditional approach to cognition focuses on the processes and structures in the mind. It argues that although a lot of cognitive tasks involve interactions with the environment, it is solely the internal mind within which all cognitive processing occurs. Thus, when an agent is faced with a task that requires interaction with the environment, the agent first creates an internal representation of the external environment through some encoding processes, then performs mental computations on the contents (symbols, subsymbols, or other forms) of this constructed internal representation, and then outputs the products of the internal processing to the environment through some decoding processes.

In contrast to the traditional view, several alternative approaches to cognition have emphasized the structures of the environment and people's interactions with them. Gibson (1966, 1979), for example, argued that the environment is highly structured—full of invariant information in the extended spatial and temporal patterns of optic arrays that can be directly picked up without the mediation of any internal representations. To Gibson, the information in the environment is also sufficient for perception and action. Situated cognition, the newly emerged view in cognitive science (e.g., Agre & Chapman, 1987; Barwise & Perry, 1983; Greeno, 1989; Lave, 1988; Lewis, 1991; Suchman, 1987), emphasizes people's relations with their environment. It argues that people's activities in concrete situations are guided, constrained, and, to a large extent, determined by the physical and social context in which they are situated. In this view, it is not necessary to construct an internal model of the environment as a mediation for situated actions: People directly access the situational information (affordances) in their environment and act upon it accordingly in an adaptive manner.

The mind is certainly important for cognition, so is the environment. The structures of the environment can guide people's behavior (e.g., in terms of affordances and constraints), and the complexity of the environment can also impose serious constraints on the information processing system of the mind, such as dense information, real time requirement, and unpredictability of the environment (Norman, 1993).

With a emphasis on both internal and external representations, this paper examines the processes in distributed cognitive tasks—tasks that require the interwoven processing of information distributed across the internal mind and the external environment, focusing on two issues: (1) the interaction between internal and external information and (2) the interplay between perceptual and cognitive processes.

DISTRIBUTED COGNITIVE TASKS

The present study is based on the framework of distributed representations, which shares the views with the situated cognition approach on the important roles of the environment in cognition.

Distributed Representations

According to the framework of distributed representations (Zhang, 1992; Zhang & Norman, in press), the representation of any distributed cognitive task is considered as a system of distributed representations, with internal and external representations as two indispensable parts. Internal representations are in the mind, as propositions, mental images, productions, connectionist networks, or other forms. External representations are in the world, as physical symbols (e.g., written symbols, beads of an abacus, etc.), or as external rules, constraints, or relations embedded in physical configurations (e.g., spatial relations of written digits, visual and spatial layouts of diagrams, physical constraints in an abacus, etc.). Figure 1 shows a distributed cognitive task that has two internal and two external representations. The internal and external representations together form a distributed representational space, which is mapped to a single abstract task space that represents the abstract properties of the task.

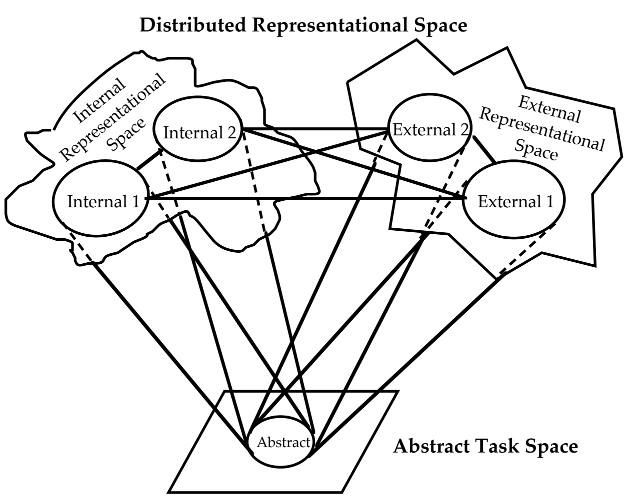

Figure 1. Distributed representations. The internal and external representations together form a distributed representational space mapped to a single abstract task space. (From Zhang & Norman, in press).

Under this framework, the medium of information processing is the distributed representational space composed of internal and external representations, not the abstract task space constructed by theorists to formulate the abstract properties of the task. To perform a distributed cognitive task is to process the information distributed across internal and external representations in an interwoven and dynamic way, not to carry out formal operations on the abstract structure of the task. The information in external representations, such as affordances and invariants, can be directly perceived without the mediation of any internal representations. The information in internal representations, however, are processed in terms of schema activation, deliberation, planning, and other high-level cognitive processes.

Structures, Representations, and Processes

Any distributed cognitive task can be analyzed into three aspects: its formal structure, its representation, and its processes. These three aspects are closely interrelated: the same formal structure can be implemented by different representations, and different representations can activate different processes.

Studying formal structures can help us capture the common structure of isomorphic tasks, which may be obscured by the different representational formats and processes that are specific to individual tasks. Studying representations can help us understand what information is to be processed and how the information to be processed is represented, e.g., what information in external representations can be directly perceived or need to be perceptually searched and what information in internal representations can be activated or need to be mentally computed. Finally, studying processes can help us understand how internal information and external information are integrated and processed and how the task is actually carried out.

One of the topics of the present paper is the analysis of the formal structures of the Tic-Tac-Toe and its isomorphs and the examination of what information is processed and how the information to be processed is represented across internal and external representations.

The Interplay between Perceptual and Cognitive Processes

Distributed cognitive tasks are accomplished by the interplay between perceptual and cognitive processes. The information in external representations has to be processed by perceptual processes. Different external representations provide different types of information and activate different perceptual processes. Some external representations provide information that can be perceived either directly or through some secondary perceptual processes such as sequential or parallel search, whereas others only provide information that has to be integrated with internal information. In the latter case, the partial information in external representations activates some internal representations, within which the remaining information can be either activated in a schema or has to be deliberately computed.

The present study examines the interplay between perceptual and cognitive processes in Tic-Tac-Toe isomorphs, in which the representational formats are manipulated to produce different perceptual and cognitive processes.

Mental Plans and Situational Strategies

To the traditional approach, planning plays important roles in cognitive tasks. To the situated cognition approach, however, people do little planning in situated tasks: They simply respond to whatever the current situations prompt them to do. Even when people do make plans in situated tasks, the plans are only one among many things produced by situated actions as secondary artifacts (e.g., Suchman, 1987). Another objective of the present study is to examine whether in performing distributed cognitive tasks people use mental plans or situational strategies.

To avoid confusion, we define a mental plan as a sequence of projected future actions formulated and computed in an internal representation. In this sense, mental planning is carried out by first establishing an internal model of the real-world situation and then in this internal model doing look-ahead and considering alternative action possibilities by means of mental computations.

Situational strategies are defined as opportunistic heuristics directly elicited by the information in the current situation without deliberate computations in any internal representations. They can be elicited either by information in the environment such as affordances and invariants, or by information in the mind such as well-formed schemas. Situational strategies are opportunistic in the sense that they only look good under the current situation: they can either lead problem solvers to or away from the goal.

There are two issues here. First, when mental planning is possible and situational strategies are available, whether people prefer one to another. Second, if people prefer situational strategies, whether it is because it is simply a preference or because mental planning is hard or impossible (e.g., due to the limited capacity of working memory).

THE TIC-TAC-TOE AND ITS ISOMORPHS

The Tic-Tac-Toe (henceforth, TTT) and its isomorphs were used in the present study to examine the processing mechanisms in distributed cognitive tasks. It is a well-known two player game. The original version is shown in Figure 2. It has eight winning triplets, which are represented by the three horizontal, three vertical, and two diagonal lines. Each player marks one square in turn in a 3×3 matrix. Whoever first occupies three squares that lie on a straight line (horizontal, vertical, or diagonal) wins the game.

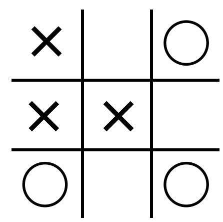

Figure 2. The original version of the Tic-Tac-Toe.

The abstract structure of the TTT is its eight winning triplets, which can be represented by any dimensional properties. Once this abstract structure is identified, an unlimited number of isomorphs of the original TTT can be generated systematically. The four isomorphs in Figure 3 were generated this way for the present study.

The equivalence of these four isomorphs is shown in Figure 4. The center, four corners, and four sides in (A) correspond to five, even numbers, and odd numbers in (B) and the big circles that have four objects, three objects, and two objects in (C) and (D), respectively. For convenience, we use five, even, and odd numbers to refer to the identical three categories of the four conditions for all later discussions.

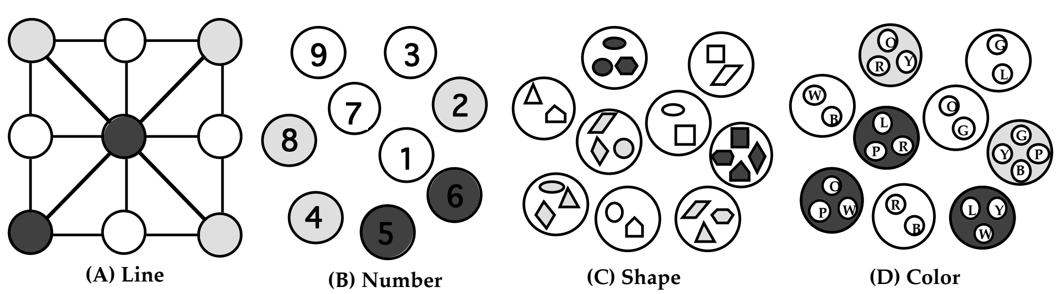

Figure 3. Four TTT isomorphs. (A) Coloring three circles on a straight line is a win. (B) The magic square. Getting three numbers that add to 15 is a win. (C) Getting three big circles that contain a common shape is a win. (D) Getting three big circles that contain the same colored small circle is a win. The letters inside the circles indicate the colors used in the experiment: B = Blue, G = Green, L = Light Blue, O = Orange, P = Pink, R = Red, Y = Yellow, W = Brown.

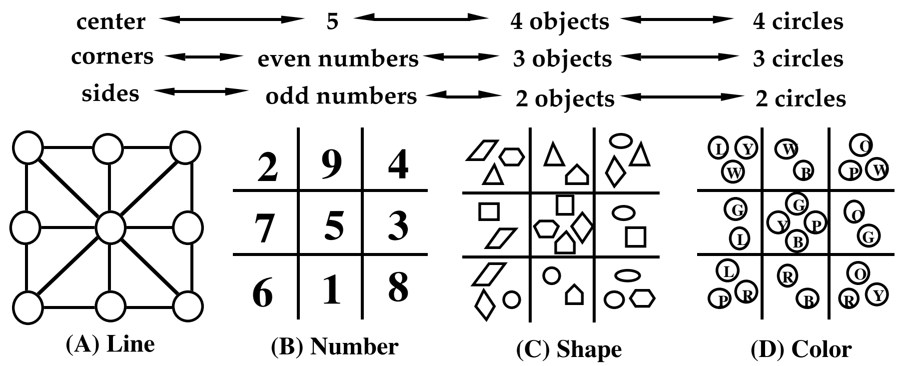

Figure 4. The mappings between the four TTT isomorphs. The center, four corners, and four sides in (A) correspond to five, even numbers, and odd numbers in (B) and the big circles that have four objects, three objects, and two objects in (C) and (D), respectively.

EXPERIMENT 1

This experiment examines two issues. The first issue is how the different perceptual and cognitive processes activated by different representations affect problem solving behavior. The second is whether in solving the TTT problems subjects rely on situational strategies elicited by the information in external and internal representations or on deliberate planning performed in an abstract problem space. If situational strategies are used, whether they improve or hinder task performance.

The four TTTs in Figure 3 were the four conditions of this experiment. In all conditions, the computer always started first by selecting an even number as its first move. The computer's strategy was carefully designed such that (a) the computer could never lose and (b) in order for the subjects to get draws, they must strictly use the following strategy to make their moves.

(1) The first move should be always five.
(2) The second move should be always any odd number.
(3) Simply block the piece that can lead to an immediate win for the computer in all later moves.

The first and the second moves are crucial: if they are not made correctly, the subjects always lose, regardless of how the later moves are made. Only in making the first and second (after the correct first move) moves did the subjects have to make selections among alternative moves. In all other situations, the subjects only have one choice, that is, blocking the piece that can lead an immediate win for the computer.

Perceptual and Cognitive Processes

The first hypothesis of this experiment is that perceptual processing of external information is more efficient than cognitive processing of internal information and parallel perceptual search is more efficient than sequential perceptual search. Thus, we have the following predictions.

In the Line version (Figure 3A), the winning triplets are represented externally by the horizontal, vertical, and diagonal lines. They can be inspected by perceptual processes. In the Number version (Figure 3B), the winning triplets are represented internally by the sums of numbers, which must be computed mentally. We predict that the Line version should be easier than the Number version because the latter may demand more resources of working memory. In addition, if planning is possible, it should be easier to do it in the Line version than in the Number version.

In both the Shape version (Figure 3C) and the Color version (Figure 3D), the winning triplets are represented externally—by different shapes and different colors. However, the colors can be searched in parallel whereas the shapes have to be searched sequentially. Thus, the Color version might be easier than the Shape version.

Mental Plans and Situational Strategies

The second hypothesis of this experiment is that in solving the four TTT problems, subjects mainly rely on situational strategies elicited by the different representations of the four problems, not on mental planning performed in an abstract problem space.

In the Line version, the invariant information is the number of lines connecting each circle: four, three, and two for the center circle, each of the four corner circles, and each of the four side circles, respectively. This invariant could elicit a situational strategy—the priority to select a circle connected by more lines, which is consistent with the required first move but not the second. We predict that subjects would have a bias to select the center circle as the first move (correct) and one of the corner circles as the second move (incorrect).

In the Number version, the nine numbers can activate various number facts (schemas) in the mind, such as large and small numbers, even and odd numbers, prime numbers, etc. However, which of these number facts is relevant to the task is not apparent. One situational strategy that seems intuitive is the priority to select large numbers, because large numbers might lead to 15 faster, which is in fact incorrect. The relevant invariant information in this case is actually the parity of numbers, which seems, however, irrelevant to the task. We predict that subjects would have a bias to select a big number as the first move, which makes five (the correct first move) less likely to be selected, and no preference over even or odd numbers for the second move.

In the Shape and Color versions, the invariant information is the number of objects in each big circle: four, three, or two, which can elicit a situational strategy—the priority to select a big circle that has more objects. We predict that subjects would have a bias to select the circle that has four objects as the first move, which is correct, and one of the big circles that have three objects as the second move, which is incorrect.

Method

Subjects

The subjects were 80 undergraduate students enrolled in introductory psychology courses at The Ohio State University, who participated in the experiment to earn course credit.

Stimuli.

The four TTT isomorphs in Figures 3 were the four conditions of this experiment. They were programmed in SuperCard on a Macintosh Quadra 700. Since the four TTTs are isomorphic, they were controlled by the same program. The computer always started first in all games by randomly selecting one of the four even numbers. The computer's strategy was designed such that it would require the subjects to discover the strategy described above in order to get draws.

A move by the computer and the person was made by a click in a circle. The pieces selected by the computer and the person were in different colors or background patterns so that they could be distinguished.

Design and Procedure.

Each subject was randomly assigned to one of the four conditions. There were 20 subjects for each condition. The instructions were given to the subjects verbally. The first part of the instructions was different for different versions and the second part was the same for all versions. The first and second parts of the instructions for the Number version are as follows:

> *"There are nine numbers on the screen. You and the computer select numbers in turn by clicking inside the circles, one at a time. Whoever first gets any three numbers that add to fifteen wins the game.*
>
> *Due to the specific design of this game, you can not beat the computer. So your task is to prevent the computer from winning, that is, to get draws. The computer always starts first. There is a strategy. If you can figure it out, you can always get a draw. You need to play this game over and over again until you get ten draws in a row."*

If a subject could get 10 draws in a row within 50 games, the experiment was over. Otherwise the experiment was over at the 50th game. All of the moves made by computer and human players and the time stamps of all moves were recorded by the computer.

Results

Overall Performance

The percentage of subjects who solved the problems within 50 games in each condition is shown in Figure 5A. The difficulty order was Line < Color < Shape = Number. The p values of χ^2 test are shown in Table 1 under the column *% Success*

The number of games needed to get ten draws in a row within 50 games in each condition is shown in Figure 5B. If a subject could not solve a problem within 50 games, to make a conservative estimate, the value was considered as 50 games. The difficulty order was Line < Color < Shape ≈ Number. The p values of Turkey HSD test are shown in Table 1 under the column *# to 10 Draws* .

The number of games needed to get the first draw in each condition is shown in Figure 5C. The difficulty order was Line < Color ≈ Shape ≈ Number. The p values of Turkey HSD test are shown in Table 1 under the column *# to 1st Draw.*

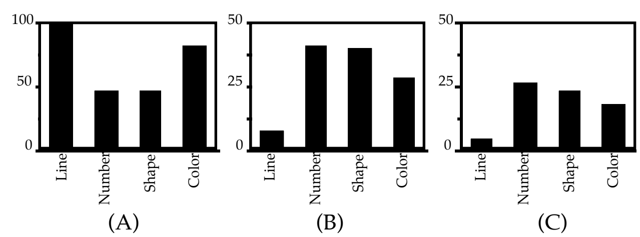

Figure 5. (A) Percentage of subjects who got 10 draws in a row within 50 games. (B) The number of games needed to get 10 draws in a row within 50 games (not including the 10 draws). (C) The number of games needed to get the first draw.

Table 1. p Values of Overall Performance

Comparisons	% Success	# to 10 Draws	# to 1st Draw
Line vs. Number	.0001	.0001	.0002
Line vs. Shape	.0001	.0001	.0005
Line vs. Color	.05	.0002	.02
Number vs. Shape	1.0	.994	.922
Number vs. Color	.05	.01	.217
Shape vs. Color	.05	.03	.555

The Pattern of Persons' First Moves

The first and second moves made by the computer and persons can be classified into three categories of five, even and odd numbers, or three categories of five, small (1 to 4) and large numbers (6 to 9). Since each subject had to play at least 10 games, we analyze the pattern of the first moves of the first 10 games played by each subject.

Distribution of persons' first moves among five, and even and odd numbers for the first 10 games. The distribution of the 10 first moves among five, even and odd numbers is shown in Figure 6A, which was averaged over the 20 subjects in each condition. The leftmost column shows the expected distribution of the 10 first moves of 10 games among five (1.25), even (3.75) and odd (5.00) numbers when there are no differential preferences over the three categories. The expected number of even numbers is smaller than that of odd numbers because the computer always started first and selected an even number as its first move.

The first comparison was among the four conditions on the selection of five's. Subjects selected "Five" more often in the Line condition than in the Number ($p < 0.0001$), Shape ($p < 0.0001$), and Color ($p < 0.003$) conditions; and more often in the Color condition than in the Number condition ($p < 0.005$). There was no significant difference between the Number and Shape conditions and between the Shape and Color conditions.

The second comparison was between observed and expected frequencies of five's within each condition. Subjects selected significantly more five's than the expected value in the Line ($t(19) = 9.969$, $p < 0.001$), Shape ($t(19) = 4.447$, $p < 0.001$), and Color ($t(19) = 4.699$, $p < 0.001$) conditions. However, There was no significant difference for the Number condition ($t(19) = 1.018$, $p > 0.20$).

The third comparison was between the frequencies of even and odd numbers in each condition. In the Line and Number versions, there was no significant difference. However, there was a strong preference over even numbers in the Shape and Color versions. The *p* values of Wilcoxon Signed Rank test are shown in Table 2.

Distribution of persons' first moves among five, and small (1 to 4) and large (6 to 9) numbers. The distribution of the 10 first moves among these three categories is shown in Figure 6B, which was averaged over the 20 subjects in each condition. The leftmost column shows the expected distribution of the 10 first moves of 10 games among five (1.25), small (4.375) and large (4.375) numbers when there are no differential preferences over the three categories.

In the Number version, there was a strong preference over large numbers as first moves. However, there was no significant difference between small and large numbers in the Line, Shape, and Color conditions. The *p* values of Wilcoxon Signed Rank test are shown in Table 2.

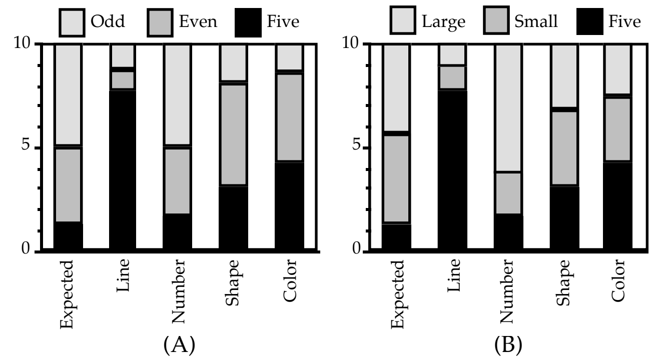

Figure 6. (A) Distributions of persons' first moves among Five, Even and Odd numbers. (B) Distributions of persons' first moves among Five, Small and Large numbers.

Table 2. *p* Values of Wilcoxon Signed Rank Test

	Line	Number	Shape	Color
Even vs. Odd	.916	.375	.0002	.0001
Small vs. Large	.638	.001	.455	.123

The Pattern of Persons' Second Moves

In order for a subject to get a draw, the first move should be always five and the second move should be always one of the four odd numbers. In this section, we show how subjects made their second moves after they correctly made the first move (five).

The distribution of moves following the first five across even and odd numbers. After five was selected as the first move for a game, a subject could select either an even or an odd number as the second move. For the first game in which five was selected as the first move, the numbers of subjects who selected even and odd numbers as their second moves are shown in Figure 7A. If subjects had no differential preferences for even and odd numbers as their second moves after the first five, the expected number of subjects who select even numbers is 13.3 (2/3 of 20) and the expected number of subjects who select odd numbers is 6.7 (1/3 of 20).

The distribution across even and odd numbers in each condition was compared with the expected distribution. There was no differential preferences over even and odd numbers in the Line ($\chi^2 = 0.0565$, $p > 0.30$) and Number conditions ($\chi^2 = 1.055$, $p > 0.30$). However, there was a marginally significant preference over even numbers in the Shape condition ($\chi^2 = 2.718$, $p < 0.10$) and a significant preference over even number in the Color condition ($\chi^2 = 5.189$, $p < 0.05$).

The distribution of moves following the first five across small and large numbers. After five was selected as the first move for a game, subjects could also select either small or large numbers as their second moves. If subjects had no differential preferences over small and large numbers as their second moves after the first five, the expected numbers of subjects who select small and large numbers are both 10 (1/2 of 20). The distribution across small and large numbers for each condition is shown in Figure 7B, which was compared with the expected distribution. There were no differential preferences over small and large numbers for all four conditions ($\chi^2 < 0.404$, $p > 0.30$, for all four conditions).

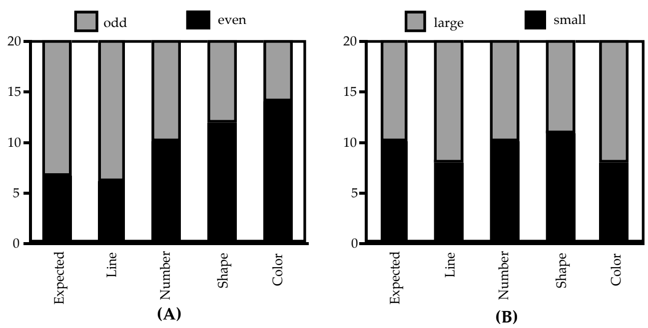

Figure 7. (A) Distribution of subjects who selected even and odd numbers as their second moves in the first game in which five was selected as the first move. (B) Distribution of subjects who selected small and large numbers as their second moves in the first game in which five was selected as the first move.

Discussion

Experiment 1 showed that the different difficulty levels of the four TTTs were mainly caused by the situational strategies elicited by the different representations of the four TTTs. The Line version was the easiest because subjects' situational strategy gave them the strongest bias to select the correct first move (five, i.e., the center circle) as the first move. In addition, subjects did not have differential preferences over even and odd numbers (corners and sides) as the second move.

The difficulty of the Number version was mainly caused by the incorrect situational strategy which made it less likely to select five (correct) as the first move. Subjects did not have differential preferences over even and odd numbers as the second move.

The difficulty of the Shape and Color versions was mainly caused by the incorrect second move (an even numbers, i.e., a big circle that has three objects) activated by the situational strategies. The different difficulty levels between the Shape and Color versions was caused by the different types of perceptual search (parallel search for the Color version and sequential search for the Shape version).

EXPERIMENT 2

If situational strategies were indeed the major factor of problem difficulty, as shown in Experiment 1, we might expect that if we change the task structure defined by the computer's strategy, we could get a different pattern of difficulty levels. This experiment examines this effect.

The same four TTTs in Experiment 1 (Figure 3) were used in this experiment. However, the task structure was changed by a different computer strategy. In this experiment, the computer still always started first. However, its first move was always five. In order for the subjects to get draws they had to strictly follow the following strategy.

(1) The first move should be always any even number.
(2) The second move should be also always any even number.
(3) Simply block the piece that can lead to an immediate win for the computer in all later moves.

Similar to the computer's strategy in Experiment 1, only in making the first and second moves (after correct first move) did the subjects have to make selections among alternative moves. In all other situations, the subjects only had one choice, that is, blocking the piece that could lead to an immediate win for the computer. Since the computer always started first and its first move was always five, the subjects could only select even or odd numbers. For this new task structure, we have the following predictions.

For the Line, Shape, and Color versions, their situational strategies are the priority to select a circle that has more choices (more line connections in the Line version and more objects in the Shape and Color versions). These situational strategies are all consistent with the first and second moves required to get draws. Thus, all these three problems should be easy. In addition, the Shape version might be harder than the Color version due to the difference between sequential and parallel search. However, there might be no difference in difficulty between the Line version and the Color venison because both cases use parallel search.

For the Number version, the situational strategy is the priority to select big numbers, which is relevant to neither the first nor the second move required to get draws. Thus, this version should be harder than the other three versions.

Method

The method of this experiment was exactly the same as that of Experiment 1, except that there were fifteen subjects in each condition and the computer's strategy was changed to the one described above.

Results

Overall Performance

All subjects in all four conditions succeeded to get 10 draws in a row within 50 games. The average number of games needed to get 10 draws in a row for each condition is shown in Figure 8A. The difficulty order was: Line ≈ Color ≈ Shape < Number. The *p* values of Turkey HSD test are shown in Table x.

The average number of games needed to get the first draw in each condition is shown in Figure 8B. The difficulty order was: Line ≈ Color ≈ Shape < Number. The *p* values of Turkey HSD test are shown in Table 3. It took more games to get the first draw for the Number version than for other three versions, which did not differ among themselves.

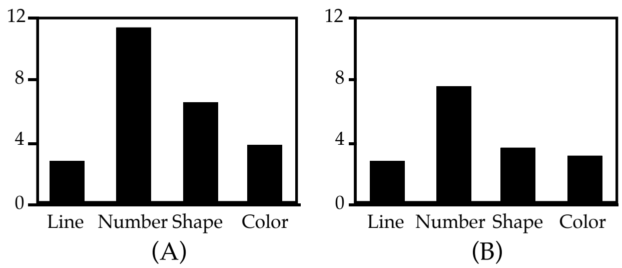

Figure 8. (A) The number of games needed to get 10 draws in a row. (B) The number of games needed to get the first draw.

Table 3. *p* Values of Overall Peformance

Comparisons	# to 10 draws	# to 1st Draw
Line vs. Number	.0006	.0003
Line vs. Shape	.254	.597
Line vs. Color	.953	.597
Number vs. Shape	.09	.009
Number vs. Color	.003	.009
Shape vs. Color	.541	1.00

Pattern of Persons' First Moves

Since it only took a few games to get 10 draws in a row in all four conditions in this experiment, it is not meaningful to analyze the pattern of first moves for the first 10 games. Thus, we analyzed the first move of the first game in each condition made by each subject and the second move of the first game in which an even number was selected as the first move. Figure 9A shows the distribution of subjects who selected even and odd numbers for the first moves in their first games. The *p* values of χ^2 test are shown in Table 5. Only in the Line version was there a significant preference over even numbers.

Figure 9B shows the distribution of subjects who selected small and large numbers for the first moves in their first games. The *p* values of χ^2 test are shown in Table 4. Only in the Number version was there a significant preference over large numbers.

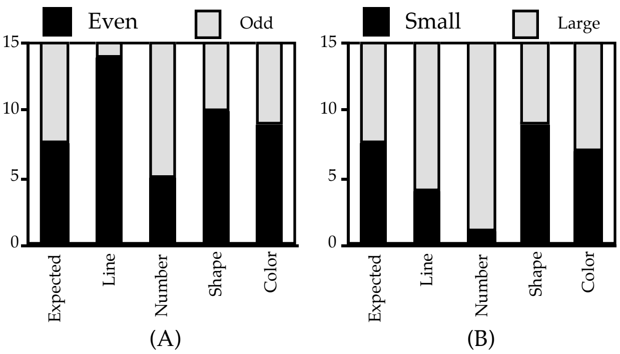

Figure 9. (A) The distribution of subjects who selected even and odd numbers for the first moves in their first games. (B) The distribution of subjects who selected small and large numbers for the first moves in their first games.

Table 4. p Values for First Moves

	Line	Number	Shape	Color
Even vs. Odd	< .01	> .20	> .20	> .20
Small vs. Large	> .10	< .01	> .20	> .20

Pattern of Persons' Second Moves

To examine the pattern of the second moves, we analyzed the second move of the first game obtained by each subject in which an even number was selected as the first move.

Figure 11A shows the distribution of subjects across even and odd numbers. The p values of χ^2 test are shown in Table 5. Only in the Shape (marginal) and Color versions was there a preference over even numbers.

Figure 11B shows the distribution of subjects across small and large numbers. The p values of χ^2 test are shown in Table 5. No condition showed a preference over large numbers.

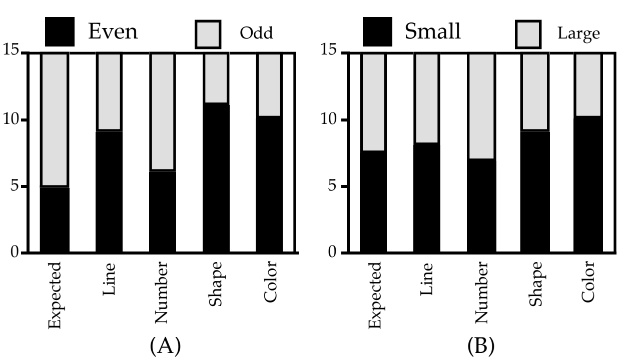

Figure 11. (A) The distribution of subjects who selected even and odd numbers for the second moves in their first games in which even numbers were selected as first moves. (B) The distribution of subjects who selected small and large numbers for the second moves in their first games in which even numbers were selected as first moves

Table 5. p Values for Second Moves

	Line	Number	Shape	Color
Even vs. Odd	> .10	> .20	< .10	< .02
Small vs. Large	> .20	> .20	> .20	> .20

Discussion

This experiment showed that with a different task structure, the pattern of difficulty levels of the four TTTs was changed.

There was no difference in difficulty among the Line, Shape, and Color versions, which were all easier than the Number version. The Line version was easy because subjects had a preference over even numbers (corner circles) as their first moves, whereas the Shape and Color versions were easy because subjects had a preference over even numbers (big circles that have three objects) as their second moves. The same difficulty level of these three versions implies that subjects' familiarity with the Line version could not be a major factor that might make the Line version easy to solve.

The Number version was hard because subjects had no preference over even numbers for either their first or their second moves. Though parallel search made the Color version a bit easier than the Shape version, the difference was not significant. In Experiment 1, there was no difference in difficulty between the Shape and Number versions. In this experiment, the Shape version was marginally easier than the Number version. This implies that the different situational strategies of the Number and Shape versions had differential effects on their difficulty levels.

GENERAL DISCUSSION

The present study showed that different distributed representations elicited different situational strategies, which were the determining factor of problem solving behavior. The difference between perceptual and cognitive processes and the difference between parallel and sequential perceptual processes also affected problem solving behavior in a significant way.

Subjects' learning behavior was not reported here due to the space limit. It has been studied in collaboration with Todd Johnson, who has been building a SOAR model of the TTT learning tasks.

Though the Tic-Tac-Toe is a simple problem, it revealed some important properties of distributed tasks, including the interaction between internal and external information and the interplay between perceptual and cognitive tasks.

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