A Dynamical Model of Insightful Memory Retrieval

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Abstract

The authors propose a dynamical model of memory retrieval that explains how people break an impasse or a memory block spontaneously without an external stimulus. We describe the process as "insightful memory retrieval". First, an experiment was conducted in which 15 participants retrieved eight Chinese characters from memory space using figural pattern cues. The results indicated that the retrieval process was divided into three phases: (1) direct retrieval, (2) indirect retrieval, and (3) an impasse and insightful retrieval. Second, a dynamical model named DIMeC was developed from the results. The direct and indirect phases depend on constraint relaxation, and the insightful retrieval phase is simulated using a chaotic neural network. Third, the DIMeC model was implemented on a computer. The results of the simulation indicate that the model reflects the typical dynamic retrieval process of the participants.

Introduction

Insight and memory block resolution are connected (e.g., Weisberg & Alba 1981; Bowers, Balthazard, & Parke 1990; Yaniv, Mayer, & Davidson 1995). Insight is characterized by spontaneity, suddenness, unexpectedness, and satisfaction (Seifelt et al. 1995), however, research into memory blocks, including the tip-of-the-tongue phenomenon, output interference, fixation, and priming effects has not shown a "spontaneous" mechanism (e.g., Smith 1995; Smith & Tindell 1997; Yaniv et al. 1995). These researchers have explained a memory block and its resolution mechanism by setting an external stimulus, such as priming. We assume that "insightful memory retrieval" expresses a spontaneous mechanism, which breaks a memory block or an impasse without an external stimulus.

An artificial neural network is one of the cognitive models that can explain the human memory system. Many models use a minimized energy function to retrieve a memory from an initial pattern, and cannot search for additional memories. Inevitably, they cannot express dynamical retrieval processes, such as retrieving one memory from another. However, Nara, Davis, & Totsuji (1993) developed a model that could travel among memories, using chaotic dynamics by controling the number of connections among units. Tani (1996) developed the "chaotic steepest descent" model, which could also travel among memories. Tani employed a nonlinear resistance to control the chaotic transition. It is interesting to apply such dynamics to the memory retrieval process of actual psychological phenomena.

Therefore, our purposes were (1) to explore how people reach an impasse and break it by insight in the memory retrieval process, (2) to develop a dynamical model using a chaotic neural network from the results, and (3) to examine the model using computer simulations.

Experiment

Method

Participants The participants were 15 Japanese graduate students at the Tokyo Institute of Technology.

Material The problem they were given was to find all the Chinese characters (Kanji) that can be made by adding one straight line to "I" without rotation, where "I" denotes the initial character in Figure 1. Eight Chinese characters can be constructed from "I". Figure 1 shows the initial character (I) and the target characters ($C_1...C_8$) and Table 1 shows the operations that must be made on the initial character to retrieve the targets. All Japanese people should have learned all these characters and the initial character in school between ages seven and fifteen years. We call the problem the ALIC (Add a Straight Line to the Initial Character) task.

Procedure Each participant was tested individually, and participants' actions and speech were recorded using a VCR. The participants were told to write down their answers on a sheet. During the session, they were urged to speak their thoughts aloud and to write, regardless of incorrect answers. When the participants indicated that they could not think of any more targets, they were told the number of remaining targets. Each session lasted until all eight targets were retrieved.

Results

Retrieval Times and Targets All the participants retrieved all the targets within 30 minutes. Figure 2 shows the retrieval patterns of the 15 participants. Each line represents the retrieval pattern of one participant. The horizontal axis indicates the cumulative number of retrieved targets and the vertical axis indicates the cumulative time. These patterns indicate that the retrieval processes were "insightful". The participants routinely retrieved five to seven targets regularly in 0 to 120 seconds, however, they could not retrieve the remaining targets for a long time; they reached an impasse (a memory

Table 2: Retrieval times for targets

Target	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Mean*	44.1	26.5	66.0	71.0	283.0	294.5	291.9	141.5
S.D.	61.5	29.3	64.3	55.1	483.4	487.0	455.1	189.2

Note: $n = 15$, *seconds

日　田　目　旧　且　甲　由　申　白

I　C_1　C_2　C_3　C_4　C_5　C_6　C_7　C_8

Figure 1: Initial (I) and target ($C_1...C_8$) characters

Table 1: Targets and operations

Target	Operation on the initial character
C_1	Add a vertical line inside I
C_2	Add a horizontal line inside I
C_3	Add a vertical line on the left outside I
C_4	Add a horizontal line under I
C_5	Add a vertical line that goes through I and protrudes from the bottom
C_6	Add a vertical line that goes through I and protrudes from the top
C_7	Add a vertical line that goes through I and protrudes from both the top and the bottom
C_8	Add a slanted line on the top of I

Figure 2: Retrieval patterns ($n = 15$)

Figure 3: Cluster tree of the targets

block developed). Then, they broke the impasse, and subsequently retrieved the remaining targets relatively quickly.

Table 2 shows the mean retrieval time and the standard diviation for the eight targets by the 15 participants. There was a relationship between the figural features of the targets and retrieval time. Targets C_1 and C_2, which are made by adding a line inside the initial character, were retrieved quickly. Targets C_3 and C_4, which are made by adding a line outside the initial character, were retrieved next. It took longer to retrieve targets C_5, C_6, and C_7, which have same added feature, a protruding line. Figure 3 shows the cluster tree for the eight targets obtained by cluster analysis using the flexible β method, where $\beta = 0.25$. Each target was clustered by retrieval time, so that the distance between targets indicates the retrieval time interval. It is clear that C_3 and C_4 were retrieved within a short interval, and the same applies to C_1 and C_2, and C_5 and C_6. These results show that the participants retrieved the targets using figural cues.

Protocol analysis The protocol data revealed that the participants repeated the following processes: (1) drawing a straight line, (2) confirming whether the character was a target. Repeating the processes, they reached the following three phases. *Phase1* (direct retrieval): 14 out of 15 participants reached this phase, and retrieved some targets without failure. *Phase2* (indirect retrieval): All the participants reached this phase, and retrieved some targets with retrieval failures, repeated retrievals, or by making writing motions with the hand without producing a visible trace. *Phase3* (impasses and insightful retrieval): 13 out of 15 participants reached this phase, and were unable to retrieve the remaining targets for a long period (over 50 seconds). In this period, they drew curved lines, added two stroks and found a Chinese char-
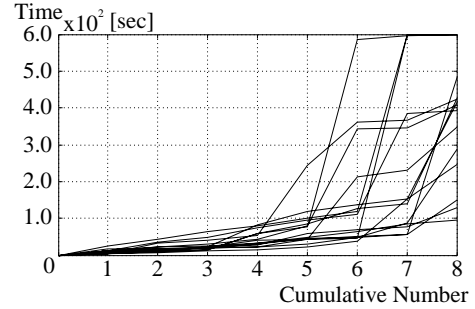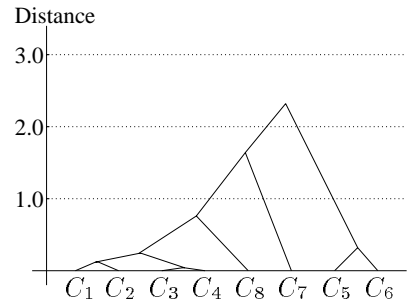
acter formed by adding two lines to the initial character, or did nothing. They failed repeatedly and their mental state fluctuated. However, they then suddenly retrieved one of the remaining targets. Once they found the figural pattern of the retrieved target, the rest were retrieved.

Table 3 shows the frequency of retrieved targets and time spent in each phase for the 15 participants. C_1 and C_2 (add inside) were retrieved mainly in *Phase1*. C_3 and C_4 (add outside) were retrieved mainly in *Phase2*. C_4, C_5, and C_6 (add protruding line) were retrieved mainly in *Phase3*. C_8 (add a slanted line) was retrieved in all phases. The duration time indicates that it took much longer to complete *Phase3* than *Phase1* or *Phase2*, so that the subjects smoothly retrieved some targets in *Phase1* and *Phase2*, with some failues, but were deadlocked for a long time in *Phase3*. This indicates that retrieving targets by adding a line inside "I" was easy, adding a line outside was relatively easy, and adding a protruding line was difficult.

Discussion

Chinese Characters for Japanese People Japanese people store Chinese characters as not only letters but also words, and they can understand their meanings from their shapes, and it is natural and routine for them. We regard the ALIC (Add a Straight Line to the Initial Character) task as similar for Japanese people to the Word Fragment Completion task (e.g., Smith & Tindell 1997) for English-speaking people in terms of making up deficiency to retrieve a word.

Table 3: Frequency of retrieved target and duration time in each phase

	Inside line			Outside line			Protruding line				Slanted line	Duration time*	
	C_1	C_2	Subtotal	C_3	C_4	Subtotal	C_5	C_6	C_7	Subtotal	C_8	Mean	S.D.
Phase1	9	12	11	2	4	6	4	4	5	13	5	23.2	15.2
Phase2	5	3	8	12	10	22	5	4	4	13	5	57.4	38.1
Phase3	1	0	1	1	1	2	6	7	6	19	5	540.3	547.6

Note: n = 15, *seconds

Retrieval with Constraint Relaxation It has been shown that there are constraints on insight problems and that insight arises when the constraints are relaxed (e.g., Hiraki & Suzuki 1998; Knoblich et al. 1999). In the ALIC task, there seemed to be stronger constraints to add lines inside and outside the initial character, and a weak constraint to add a protruding line. Their strength seemed to change with repeated failure as the retrieval process progressed. When the constraints were relaxed, the participants could retrieve the remaining targets by insight.

Model

Hypothesis of the Model

Retrieval Process and Constraint Relaxaion Hiraki & Suzuki (1998) maintained that the problem can be expressed by three components (object, relation, and goal), where each component has a constraint, and that insight problems are solved by cooperation among the components and with relaxing their constraints, which triggers a representation change. We assume that memory retrieval processes in the direct and indirect phases depend on the relaxation of constraints (object and relation), evaluated by the goal constraint.

Insightful Retrieval with Chaotic Process Finke & Bettle (1996) maintained that insight is spontaneous, and occurs at levels of processing that lie below conscious awareness and control of the underlying process, which characterizes chaotic thinking, and that a chaotic process can often be employed when normal pathways are blocked. Then, we assume that chaotic dynamics explain the insight process.

Conscious and Unconscious Layer Since Finke & Bettle (1996) maintained that a chaotic process is employed without awareness when logical strategies fail, we developed a model including conscious and unconscious layers. The former characterizes direct and indirect retrieval and the latter characterizes an impasse and insightful retrieval. In the conscious layer, a strategic process generates an image by adding one straight line to the initial character "*I*", and then the image is sent to the unconscious layer. In the unconscious layer, the memory space associates the image and the retrieved result is sent to the conscious layer, where it is evaluated. Strategic procedures fail with repeated retrieval failure, so a chaotic retrieval process is then employed in the unconscious layer. Consequently, the state of the memory space repeats the chaotic transition and retrieves the remaining targets by insight.
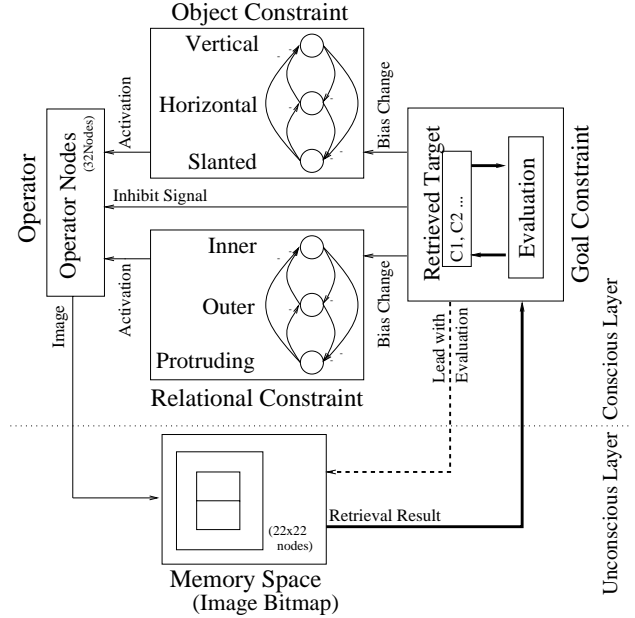

Figure 4: The DIMeC model

Retrieval Process

Figure 4 illustrates the model. We named the model "DIMeC" (Dynamical model of Insightful Memory retrieval with Constraint relaxation). Narrow solid lines are enabled only when a strategic process is employed, the dashed line is enabled only when a chaotic process is employed, and bold solid lines are enabled all the time.

DIMeC repeats the following four steps: it generates an operator to draw a straight line; it generates an image by adding the line to the initial character; it associates the image with memory space and retrieves the result; and it evaluates the result. This process retrieves some targets and this period includes *Phase1* and *Phase2*.

After retrieving some targets, an impasse arises, with constraint relaxation because of repeated retrieval failure. Then, the chaotic process is employed and the remaining target is retrieved by insight. This period is *Phase3*.

Definition of Memory Space

The image generated by the operator is associated with the memory space to be evaluated. The memory space is defined by learning Chinese characters with the Hebb rule, and representing their shape on a 22×22 pixel image bitmap, where one unit represents one pixel. We employ a Hopfield network (Hopfield & Tank 1985) where the internal state of the ith unit is defined as x_i,

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$$\frac{dx_i}{dt} = -\frac{x_i}{\tau} + \epsilon \left(\sum_k w_k u_i + \theta_i \right) \qquad (1)$$

where $\tau > 0, \epsilon > 0$ and θ_i is the threshold of ith unit. The output of the ith unit is defined as u_i,

$$u_i = \frac{2}{1 + e^{-\alpha x_i}} - 1 \qquad (2)$$

where $\alpha > 0$. The energy function of the memory space is defined as E,

$$E = -\sum w_{ij} u_i u_j \qquad (3)$$

where w_{ij} is the connective weight between the ith and j^{th} units. The weight is based on the one-year frequency data for Chinese characters in the daily *Asahi Shimbun* (Nozaki et al. 1996). Only the initial character and the eight targets are trained.

Retrieval with Constraint Relaxation
As mentioned above, the retrieval process in the direct and indirect phases depends on constraint relaxation (object and relation). In the ALIC task, the object constraint consists of three elements (horizontal, vertical, and slanted) and the relational constraint consists of three elements (inside, outside, and protruding). Table 4 shows the relationship between constraints and targets. The goal constraint is not relaxed, but evaluates the result of retrieval and acts on the object and relational constraints.

Relational and Object Constraints A Hopfield network (Hopfield & Tank 1985) is employed to represent object and relational constraints, which are called object and relational constraint networks, respectively. One unit is introduced for each constraint element, and each inhibits the others within each network. The strength of each constraint is represented by its threshold. The initial state of the unit is set to zero, and the network repeats the transition, minimizing the energy function. After it stabilizes, an operator corresponding to the output of the constraint networks generates an image by adding a straight line to the initial character. The operator consists of 32 units, previously defined with the protocol data of the experiment. The output of operator $\mathbf{q}$ is calculated by the transformation matrix $\mathbf{W}$,

$$\mathbf{q} = \mathbf{W} \begin{bmatrix} \mathbf{Z} \\ \mathbf{R} \end{bmatrix} \qquad (4)$$

where $\mathbf{Z}$ is the output of the object constraint network and $\mathbf{R}$ is the output of the relational constraint network. Then, the memory space assosiates the image and the result is retrieved.

Goal Constraint As mentioned above, the goal constraint evaluates the retrieval result and acts on object and relational constraints. There are five functions
(a) When a target is retrieved, the goal constraint sends an inhibitory signal $\mathbf{G}$ to the units of the operator corresponding to the previous operation,

Table 4: Targets and constraints

Target	Object			Relation		
	ver.	hor.	sla.	inn.	out.	pro.
C_1	+	-	-	+	-	-
C_2	-	+	-	+	-	-
C_3	+	-	-	-	+	-
C_4	-	+	-	-	+	-
C_5	+	-	-	+	-	+
C_6	+	-	-	+	-	+
C_7	+	-	-	+	-	+
C_8	-	-	+	-	-	+

Note: + indicates positive and - indicates negative

$$\mathbf{G} = -\mathbf{T}\mathbf{A} \qquad (5)$$

where $\mathbf{A}$ is the retrieved target vector and $\mathbf{T}$ is the transformation matrix from the target to the inhibitory signal. Consequently, in the next operation, a different operator with the same constraints generates an image.
(b) In the case of repeated retrieval of a target, the constraints corresponding to the previous operation are relaxed by,

$$\frac{\partial \mathbf{\Theta}}{\partial t} = -\zeta_r \mathbf{s} \qquad (6)$$

where $\zeta_r > 0$, $\mathbf{\Theta}$ is the strength of the constraints (i.e., threshold vector of the object and relational constraint networks), and $\mathbf{s}$ represents the relaxed unit.
(c) In the case of retrieval failure (i.e., finding no Chinese characters), the constraints corresponding to the previous operation are relaxed by using equation (6) and replacing ζ_r with ζ_f where $\zeta_f > 0$.
(d) In the case of an impasse, the state transition in the memory space is led by an evaluation function. Details are presented in the following section.
(e) In the case of an insightful retrieval, constraints corresponding to the figural pattern of the target are strengthened,

$$\frac{\partial \mathbf{\Theta}}{\partial t} = \zeta_s \mathbf{V}\mathbf{A} \qquad (7)$$

where $\zeta_s > 0$ and $\mathbf{V}$ is the transformation matrix from the target vector to the figural pattern vector.

Impasses and Insightful Retrieval
Impasses and insightful retrieval processes arising in the memory space are simulated using the "chaotic steepest descent" (CSD) model (Tani 1996) led by an evaluation function.

Chaotic Transition Tani (1996) developed the CSD model with a neural network employing a nonlinear resistant f_i for the ith unit.

$$m\ddot{x}_i + f_i(\dot{x}_i, t) = -\epsilon \frac{\partial E}{\partial u_i} \qquad (8)$$

$$f_i(\dot{x}_i, t) = (d_0 \sin \omega t + d_1)\dot{x}_i + d_2 \dot{x}_i^2 \text{sgn}(\dot{x}_i)$$

where $m > 0, \epsilon > 0, d_0 > 0, d_1 > 0, d_2 > 0, \omega > 0$, u_i is the output of the ith unit, x_i is the internal state of the ith unit, $\ddot{x}$ is the acceleration of x, and $\dot{x}$ is the velocity of x. With this model, Tani showed that the state of the network travels from one energy basin to another
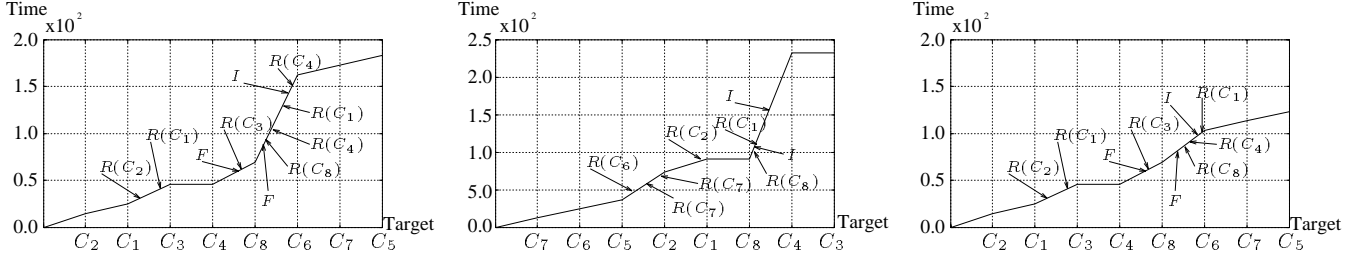
Figure 5: Retrieval patterns   simulation 1 (left);   simulation 2 (center);   simulation 3 (right)

with chaotic dynamics as the resistance characteristics change from positive to negative, and the transition pattern corresponds to the cluster tree of the memory pattern. We employ the CSD model to simulate traveling among memories in an insightful retrieval process.

Transition by Evaluation Function   Smith (1995) maintained that metacognitive monitoring towards a goal was often predictive of impending success. We have developed a metacognitive evaluation mechanism, similar to that which Nakagawa (1987) used to explain avoidance behavior by maximizing the evaluation of a psychological measure,

$$E_v \quad = \quad \sum_k \gamma_k \log \|\mathbf{u_k} - \mathbf{u}\|^2 \qquad (9)$$

where $\gamma_k > 0$, $\mathbf{u_k}$ is an already retrieved target vector, and $\mathbf{u}$ is the internal state vector in memory space. The value of the evaluation gets larger as the state in the memory space gets further from targets already retrieved.

As a result, we obtain the dynamics of the insightful retrieval, which can go from one memory to others as maximizing the evaluation,

$$m \ddot{x}_i + g_i(\dot{x}_i, x_i, t) \quad = \quad -\epsilon \frac{\partial E}{\partial u_i}$$

$$g_i(\dot{x}_i, x_i, t) \quad = \quad f_i(\dot{x}_i, t) + \beta \frac{\partial E_v}{\partial x_i} \qquad (10)$$

where $\beta > 0$.

Simulation

Method
The threshold vecters that represent the object and relational constraints at t are expressed as:

$$\Theta(t) = [\ \theta_v \quad \theta_h \quad \theta_s \quad \theta_i \quad \theta_o \quad \theta_p \ ]^T \qquad (11)$$

where $\theta\{v|h|s|i|o|p\}$ represents the strength of vertical, horizontal, slanted, inner, outer, or protruding constraints, and the notation "T" indicates transposed.

Simulation 1   The default constraint $\Theta(0)$ was set as:

$$\Theta(0) = [\ 2.0 \quad 2.0 \quad 1.0 \quad 1.5 \quad 1.0 \quad 0.5 \ ]^T \qquad (12)$$

In this condition, the vertical and horizontal constraints were stronger than the slanted constraint; the inner constraint was stronger than the outer constraint; and the outer constraint was stronger than the protruding constraint. The other parameters were as follows: $\tau = 1.0$,

$\epsilon = 1.0 \times 10^{-3}$, $\alpha = 3.0$, $\zeta_f = 0.2$, $\zeta_r = 0.8$, $\zeta_s = 1.0$, $m = 1.0$, $\omega = \pi/20$, $d_0 = 4.0$, $d_1 = -4.0$, $d_2 = 4.95 \times 10^1$, $\beta = 1.0 \times 10^{-3}$, $\gamma = 1.2 \times 10^1$.

Simulation 2   The default constraint $\Theta(0)$ was set as:

$$\Theta(0) = [\ 2.0 \quad 0.5 \quad 0.5 \quad 1.5 \quad 0.0 \quad 3.0 \ ]^T \qquad (13)$$

In this condition, the vertical constraint was stronger than the horizontal and slanted constraints; the protruding constraint was stronger than the inner constraint; and the inner constraint was stronger than the outer constraint. The other parameters were the same as in simulation 1.

Simulation 3 d_2 was set to 4.0, and the other conditions were the same as in simulation 1.

Results and Discussion
Figure 5 shows retrieval patterns of simulations 1, 2, and 3. The horizontal axis indiates the retrieved target, the vertical axis indicates cumulative time, $R(C_n)(n = 1, 2...8)$ denotes the repeated retrieval of $C_n(n = 1, 2...8)$, F denotes retrieval failure, and I denotes the initial character. These patterns are similar to Figure 2. The retrieval patterns of the simulation reflected the typical retreival patterns of the participants, because (1) each result could be divided into three phases, (2) targets with a figural pattern corresponding to strong constraints were retrieved first and weak ones were retrieved later, (3) targets with the same figural patterns were retrieved within a short interval, and (4) the retrieval process reached an impasse, and broke it insightfully by chaotic transition.

Simulaion 1 C_2 (add inside) was retrieved at $t = 14.3$ and C_1 (add inside) was retrieved at $t = 24.7$ because of the strong inner constraint. This period represents *Phase1* (direct retrieval).

C_2 was retrieved again at $t = 35.2$ and C_1 was retrieved again at $t = 45.6$, so the vertical, horizontal, and inner constraint were relaxed (i.e., the outer constraint became relatively stronger). As a result, C_3 (add outside) was retrieved at $t = 45.7$ and C_4 (add outside) was retrieved at $t = 45.8$. Retrieval failed at $t = 57.7$ and C_4 was retrieved again at $t = 57.8$, so the horizontal, vertical, and outer constraints were relaxed. Since the protruding and slanted constraints became relatively stronger, C_8 (add slanted) was retrieved at $t = 68.8$. This period represents *Phase2* (indirect retrieval with

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repeated retrieval of some targets and retrieval failures).

After a retrieval failure at $t = 78.9$, C_8 was retrieved again at $t = 79.5$, so the slanted and protruding constraints were relaxed. Then, the strategic process failed, and the chaotic process was employed. The state in the memory space traversed C_4, I, C_1, and C_4. Traveling among memories, C_6 (add protruding) was retrieved at $t = 162.3$. Having retrieved C_6, the protruding constraint became stronger. Therefore, the chaotic transition stopped and strategic process was employed again. Consequently, C_5 (add protruding) was retrieved at $t = 172.7$ and C_7 (add protruding) was retrieved at $t = 182.8$ because of the stronger protruding constraint. Retrieving all targets, the retrieval process ended. This period represents *Phase3* (impasses and insightful retrieval).

Simulaion 2 C_7, C_6, and C_5 (add protruding) were retrieved first because of the strong protruding constraint, then C_2 and C_1 (add inside) were retrieved. Because the outside constraint was weak, C_4 and C_3 were not retrieved by the strategic process in *Phase1* or *Phase2*, but were retrieved by the chaotic process in *Phase3*.

Simulaion 3 In *Phase1* and *Phase2*, the retrieval process was the same as in simulation 1, but C_7, C_6, and C_5 were retrieved earlier than in simulation 1 by the chaotic process in *Phase3*, because the retrieval process traveled among memories more often. This was caused by the smaller value of the nonlinear resistant coefficient d_2, which corresponds to the result of Tani (1996).

General Discussion

Research into memory blocks has shown its process by setting an external stimulus (e.g., Smith 1995; Smith & Tindell 1997; Yaniv et al. 1995). We examined the dynamic spontaneous process of its resolution, and showed that the retrieval processes are similar to insight with constraint relaxation. We think that insight and memory block resolution can be explained by the same mechanism, even though representational change or information retrieval can explain the process of insight. The DIMeC (Dynamical model of Insightful Memory retrieval with Constraint relaxation) was developed, depending on constraint relaxation and a chaotic neural network. Therefore, we consider that the DIMeC architecture can be applied to the dynamic insight process.

Human memory has been explained using a neural network model based on its parallelism and distributive representation. Too much interest in this has prevented the development of a dynamical model of memory retrieval, although the human cognition process essentially consists of both parallel and sequential processes. The DIMeC model is a hybrid system that has both parallel and sequential mechanisms, enabling it to explain dynamical processes. It also refers to the conscious and un-conscious, and can explain the priming effect, TOT phenomenon, output interference, and other memory block phenomena.

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