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Authors
Suzuki, Hiroaki
Abe, Keiga
Hiraki, Kazuo
et al.

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Hiroaki Suzuki (susan@ri.aoyama.ac.jp)
Keiga Abe (a1297007@cc.aoyama.ac.jp)
Department of Education, Aoyama Gakuin University
Tokyo 150-8366 JAPAN
Kazuo Hiraki (hiraki@idea.c.u-tokyo.ac.jp)
Department of Systems Science, The University of Tokyo
Tokyo, 153-8902
Michiko Miyazaki (miyazaki@psyche.tp.titech.ac.jp)
Tokyo Institute of Technology
Tokyo, 152-8552 JAPAN

Abstract

This paper explores a mechanism underlying cue-readiness in insight problem-solving. Cue-readiness is concerned with situations where previously neglected information suddenly and unexpectedly becomes illuminative. From the view point of dynamic constraint relaxation theory (Suzuki & Hiraki, 1997), this can be explained by constraint relaxation caused by noticing failures. The theory predicts that constraint violations increase during the problem-solving process, and that a specific combination of constraint violations takes place which leads people to an insight. In this paper, we examined the time-course differences of frequencies of constraint violations, and of sensitivity to the crucial information using a rating task. Although Experiment 1 did not provide supporting evidence, in Experiment 2 we found increased frequency of constraint violations during problem-solving, and that subjects who experienced more failure were more sensitive to crucial information. These results are discussed in terms of other theories of insight.

Insight, one of the most outstanding cognitive activities, is more and more a topic within the scope of rigorous scientific investigation. For the past decade, various approaches have been taken to explore the nature and processes of insight (see, for example, Sternberg & Davidson, 1995).

However, there still remains a mystery. People sometimes find a crucial cue in a relative early stage of problem-solving, but they cannot make use of it. This cue, however, suddenly and unexpectedly becomes illuminative at a certain point, leading problem-solvers to an insight. To put it another way, the same cue has different meanings during the problem-solving process. This can be called "cue-readiness" because it appears analogous to developmental readiness in that the effectiveness of instructional intervention depends on the child's developmental stage.

A good example of the cue-readiness is found in Kaplan and Simon (1990). They used the mutilated checkerboard (MC) puzzle as a material. To solve this puzzle, it is crucial to realize the parity of differently colored squares. In order to control the ease of noticing parity, some subjects in their experiment were given a special board where a word, Bread or Butter, was printed on each square (bread and butter connote parity), instead of colors black or pink. As they predicted, subjects noticed parity more easily and solved the puzzle more quickly. However, they reported one puzzling result. The times from their first mention of parity to the final solution were longer for these subjects than those who were given a standard checkerboard or blank one. While subjects with a Bread–Butter board took 653 s on average to solve the puzzle from their first mention of parity, those with a standard checkerboard took only 110 s.

The problem immediately poses the questions of why people can make use of the crucial cue that they could not do so initially, and what distinguishes the internal states in these two situations.

This problem cannot easily be explained by current theories. Theories based on spread of activation presuppose that the inappropriate problem representations prevent problem-solvers from retrieving an important cue. If this explanation is correct, people could solve the puzzle immediately after noticing the important cue, because the representation of the cue should be activated and the activation spreads over to related information. In the MC puzzle case, subjects could obtain an insight immediately after they mentioned parity.

The idea of the prepared-mind proposed by Seifert et al. (1995) appears to be relevant to the cue-readiness problem. According to them, when people find a standard approach inappropriate, they generate failure indices that mark initial problem solving attempts as unsuccessful. These failure indices are presumed to have the special status in long-term memory, in the sense that they are activated for a longer period than other types of memory traces. In the incubation phase where people stop their initial attempts and are engaged in other activities, a relevant cue is sometimes provided externally, which reminds them of their initial failure and leads them to an AHA experience. We agree that failure and externally provided information play important roles. However, this idea cannot be applied directly to the cue-readiness problem, because their idea deals with a situation where people do not encounter or find crucial information in the initial phase but are given that information externally in the incubation phase. The cue-readiness problem is, however, concerned with a situation where people find crucial information in the initial stage.

In order to deal with the cue-readiness problem, we have developed a dynamic constraint relaxation theory of insight (Suzuki & Hiraki, 1997; Hiraki & Suzuki, 1998).

In the next section, we briefly illustrate the theory.

Dynamic Constraint Relaxation

The dynamic constraint relaxation theory consists of three kinds of constraints (object-level, relational, and goal), and a relaxation mechanism. The main idea is that impasses are formed by these constraints and that qualitative changes are caused probabilistically by the failure-driven incremental relaxation of these constraints.

Constraints

Since it is unlikely that we are equipped with a special cognitive engine for insight problem-solving, it would be desirable that theories of insight do not involve insight-specific mechanisms. One of the most important findings in problem-solving research is that people construct a problem representation consisting of objects, relations, and a goal of the given problem. Reflecting on these findings, we postulate three constraints with objects, relations, and goal. Although the notion of constraints in insight literatures is not new (Isaak & Just, 1995; Knoblich et al., 1999; ; Ohlsson, 1992), our treatment is different from theirs and very similar to analogy (Holyoak & Thagard, 1995).

Object-level constraint There are numerous ways of encoding objects. However, we have a natural tendency to encode them at a basic level (Rosch, 1978). This tendency sometimes becomes an obstacle for insight. For example, in the "Candle" problem, it is well known that people do not notice a pasteboard box of tacks as a holder of the candle. This is because the basic level of a box is "box," not a "solid body" (more abstract) or a "pasteboard box" (more concrete).

We call this tendency the object-level constraint, because it constrains, among possible alternatives, the selection of a specific encoding of a single object. Note here that the constraint is a soft one. It is not that this constraint precludes any other encodings.

Relational constraint Relations define the ways in which objects relate to one another, and each object is assigned a specific role within the relation. Usually, one can relate something to others in various ways. The box in the candle problem, for example, can interact with others in ways of containing, standing on, being thrown to, other objects. However, people usually select the "contain" relation as its default relation.

We call this tendency the relational constraint, because it leads people to select specific relations among numerous alternatives. This constraint is, like object-level constraint, a soft one.

Goal constraint The representation of a goal involves the desired state and evaluation function. This constraint evaluates a match between present and desired states, and gives feedback to the other constraints. Thus, the goal greatly constrains how objects and relations are represented. Although a relation of a candle to other objects is, by default, to light something, a relation such as to glue something by its wax is likely to be selected by the goal constraint.

It is important to note that these constraints interact each other. For example, one reason why the "tacking" relation is selected for the tack is that the basic level encoding of the tack enhances this selection. Another reason is that the goal constraint prevents them from being thrown.

In ordinary problem-solving, these constraints play important roles by eliminating an infinite number of useless representations. However, as noted above, they operate in a harmonious way to form an impasse in insight problem-solving.

Relaxation mechanism

It is important to note that each constraint is not constant during problem-solving, but that its strength changes dynamically. In the course of problem–solving, the mismatch computed by the goal constraint decreases the strengths of initially dominant constraints, which leads to an increase in the probability of constraint-violations. When specific constraint violations occur simultaneously at object-level and relational level, people reach an insight.

In this constraint relaxation process, failure or mismatch detected by the goal constraint plays a key role. A current computational model uses a sort of Q learning algorithm to relax the constraints (Hiraki & Suzuki, 1998). The basic idea is that the strength of the constraint responsible for the failure is reduced to some degree and that the amount of the reduction is distributed to other less dominant constraints by the softmax algorithm (Bridle, 1989).

The dynamic constraint relaxation theory owes much to the multiconstraint theory of analogy (Holyoak & Thagard, 1995). Types of constraints are similar between the two. This is partly because both theories are based on the general characteristics of human problem-solving. However, a crucial difference is that multiconstraint satisfaction often leads to a fruitful analogy, whereas constraint violation leads to an insight in insight problem-solving. Another important difference is that whereas constraint relaxation is purely internal in ARCS and ACME, our theory presumes dynamic interaction with the external environment via feedback.

Previous Studies

We used the T puzzle, similar to the tangram, as material. The goal of this puzzle is to construct the shape of a "T" using four pieces depicted in the left side of Figure 1. At first glance, it appears quite easy to solve, since there are only four pieces and one can easily identify possible positions that some of them should be placed. However, a pilot study, in addition to our own experiences, showed that it is awfully difficult. It usually takes more than half

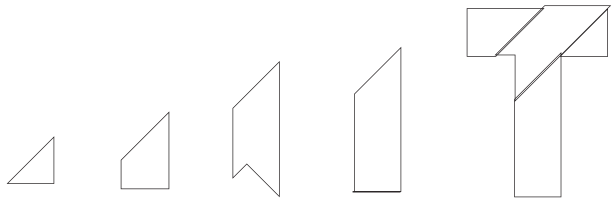

Figure 1: The T puzzle: Construct a shape of "T," using four pieces on the left side.

an hour to solve it spontaneously. Furthermore, more than a few give up trying to solve it.

The difficulties can be explained by the constraints described in the previous section. The object-level constraint in this puzzle is concerned with the preference for how a single piece should be placed, because pieces are objects in the problem representation. People have a strong tendency to place the pentagon piece either horizontally or vertically (Suzuki & Hiraki, 1997). A previous study revealed that subjects placed this piece horizontally or vertically in about 70% of their trials.

The relational constraint in this puzzle is concerned with how one piece is physically connected to one another. The puzzle of this type has an infinite number of relations, because one can produce different patterns by sliding a side of a piece touching another. But, again, people have a strong tendency to connect pieces so as to form a "good" shape with fewer angles. If this constraint actually operates with the goal constraint that evaluates the difference between the current shape and the image of T, it is predicted that people spend most of their time filling the notch of the pentagon. The prediction was confirmed by a previous study which showed more than 70% of the subjects' trials involved notch filling.

Experiment 1

Since our theory predicts that the frequency of constraint violation increases during problem-solving by noticing failure, we analyzed the time-course of constraint violation in Experiment 1. Another dependent variable was subjects' rating score. We used a rating task where subjects evaluated the closeness of various types of combinations of two pieces to the goal. The rating materials were a set of combinations of the pentagon and one of the other pieces, produced by systematically violating the constraints. To control the degrees of relaxation, we divided subjects into two groups, 2-min and 7-min conditions. Subjects were required to solve the puzzle for two or seven minutes, then proceeded to the rating task.

Since subjects in the 7-min condition have failed more often than those in 2-min condition, the theory predicts that the degree of relaxation is higher in the former than in the latter (this is an empirical issue to be examined later). If so, their ratings should be different. According to the theory, the 7-min subjects are more sensitive to crucial information in the rating stimuli than the 2-min subjects. Hence, we expect a statistical interaction between the types of stimuli and before-rating times (2- and 7-min).

Method

Subjects Participants were 33 undergraduate students without any prior experience to solve the T puzzle. They were randomly assigned to 2-min or 7-min condition. We omitted subjects who solved the puzzle before the rating task. Resulting 26 subjects (12 in the 2-min and 14 in the 7-min conditions) were analyzed.

Rating Materials The rating materials consisted of 12 combinations of the pentagon and one of the other pieces (big, small trapezoids, or triangle). These combinations formed four types: O–R– where neither constraints were violated, O–R+ where not object-level, but relational constraint was violated, O+R– where the violating pattern was reversed, and O+R+ where both constraints were relaxed. Since each type had three members depending on which piece was used (big, small trapezoids, or triangle), the total number of rating stimuli was 12.

Procedure The subjects were given the four pieces of the T puzzle and a sheet of paper printed with a 25% reduced-size image of a constructed T. Subjects were asked to construct the shape of "T" using the pieces, with the information about the time allowed to spend before the rating task (2 or 7 minutes).

In the rating task, they were told to rate how close a presented stimulus was to the shape of T with respect to the goal of constructing T, and to click "10" if the stimulus was very close, "0" if it was far from the goal, and other numbers for the intermediary degrees of closeness. Stimulus was presented in a semi-random order that stimuli belonging to the same type were not presented successively. Stimulus presentation time was two seconds, and time for the rating was five seconds.

After completing the rating task, the subjects were asked to resume solving the puzzle. If subjects could not solve the puzzle within 10 minutes from the beginning, the experimenter gave subjects the first hint not to fill the notch of the pentagon (the hint for the violation of the relational constraint). When subjects could not solve the puzzle within five minutes after the first hint, the experimenter gave the second hint not to place the pentagon horizontally or vertically. The entire problem-solving processes were video–taped for the later analysis.

Results and Discussion

To analyze the problem-solving performance, we used a segment as a unit of analysis, in addition to the solution time. A segment is operationally defined as a series of actions that was initiated by physically joining two pieces and terminated by their separation. A segment roughly corresponds to a trial that begins with trying an approach and ends up with noticing failure. It is worth noting that the notion of segment is not a subjective one, because the definition is based only on physical connections and separations of pieces.

Constraint violation To analyze the time-course of constraint violation, we divided problem-solving processes into four phases, based on the segments (segments after the hints were not included). We counted a segment as a violation of object-level constraint, if the segment did not include the horizontal or vertical placement of the pentagon. We counted a segment as a violation of the relational constraint, if the segment did not have actions to fill the notch of the pentagon by other pieces. Since we found no difference between the two conditions, we merged data obtained from 2- and 7-min conditions. Table 1 shows the proportions of constraint violations in each phase. We conducted one-way ANOVAs for the violation of each constraint separately. We could not find significant time-course difference in the number of segments where the constraints were violated.

Table 1: The percentages of constraint violation in each phase.

	1/4	2/4	3/4	4/4
object-level constraint (%)	24	21	25	25
relational constraint (%)	36	38	38	46

Presenting various types of stimulus did not have a strong effect on the problem-solving performance. The proportions of subjects who solved the puzzle within three minutes after the rating task were 25% in the 2-min condition, and 28.6% in the 7-min condition. These results suggest that majority of the subjects were unable to utilize the useful information presented in the rating task. Additionally, the solution times were not different between the two conditions ($U_{2-min}(12,14) = 66, ns.$).

Rating Before analyzing the rating task data, it is necessary to examine the assumption about constraint-relaxation. Our theory predicts that the more often subjects fail, the more relaxed their constraints are. Hence, we must first examine whether the subjects in the 7-min condition actually failed more often before the rating task than those in the 2-min condition. As we expected, the average number of the segments before the rating task in the 7-min condition was 45.6, while that in the 2-min condition was 17.4 ($t(24) = 7.79, p < 001$).

Table 2 shows the rating score for each type of stimulus. Although the ratings for R–O–, R–O+, R+O– were not different between the two groups, it appears that the 7-min subjects rated the R+O+ type stimuli closer to the goal than the 2-min subjects did. Thus, we conducted a three-way ANOVA to examine the interaction between the types of the stimulus and the conditions. However, the interaction did not reach the significant level ($F(3,72) < 1, ns.$), although there was a main effect of the stimulus types ($F(3,72) = 10.93, p < 005$). Pair-wise comparisons revealed that for both conditions, the R+O+ type was rated closer to the goal than the other types.

Table 2: Mean rating score.

	R–O–	R–O+	R+O–	R+O+
2-min	2.73	2.96	3.90	4.29
7-min	2.83	3.04	3.94	5.35

Experiment 2

The results of Experiment 1 did not support the hypotheses. We found no time-course difference in the frequencies of constraint violations. Furthermore, there was no statistical interaction between the rating scores and the problem-solving time before the rating task. Do these results dismiss the dynamic constraint relaxation theory?

There is, however, the possibility that even for the 7-min subjects, the constraints were less relaxed than expected. According to our theory, one reason is concerned with the goal constraint. As described earlier, the goal constraint plays crucial roles by evaluating the match between the goal and the present state and by giving feedback to the constraints for their relaxation. Actually, previous research revealed that the goal constraint greatly facilitated problem-solving performance (Suzuki et al., 1999). In that experiment, some subjects were given a template sheet printed with an image of a constructed "T," and asked to cover the image by placing the four pieces. Providing the template sheet is expected to facilitate the evaluation of the (mis)match between a current state and the goal. As expected, these subjects solved the puzzle significantly faster than those without the template sheet.

In Experiment 1, subjects were given a sheet of paper printed with an image of "T," but the size was reduced to 25%. In addition, the subjects were not allowed to put the pieces on the sheet. This procedure may cause the goal constraint to operate less effectively. Experiment 2 explores this possibility, by providing the template sheet and instructing subjects to cover the sheet by the pieces.

Method

Subjects Subjects were 20 undergraduate students who had no experience with the "T" puzzle. None of them participated in the previous experiment. These subjects were randomly assigned to either the 1-min or 5-min condition. We omitted three subjects in the 1-min condition and one subject in the 5-min condition who solved the puzzle before the rating task.

Materials The rating materials were 12 combinations of the pentagon and one of the other pieces used in Experiment 1.

Procedure The procedure was basically the same as that of Experiment 1, but there were two modifications.

The first one was to provide subjects with a template sheet printed with an image of "T" and to ask them to cover the image by placing the four pieces. The second one was that the time to solve the puzzle before rating was changed from two and seven to one and five minutes. This was because in a previous study, half of the subjects with the template sheet solved the puzzle within seven minutes.

Results and Discussion

Constraint violation To examine the time course of constraint-violation, we divided the entire problem-solving processes into four phases and counted the number of violations in each quarter, as for Experiment 1. We omitted segments after the hints and merged data obtained from 1- and 5-min conditions. Although the increase of the violation of the relational constraint was not statistically significant ($F(3,48) = 1.07, ns.$), the number of violations of object-level constraints increased dramatically ($F(3,48) = 7.89, p <. 001$). Pair-wise comparisons revealed that the violations of object-level constraints in the final quarter was higher than the others.

The lack of an increase in the number of the relational constraint violations might be due to the fact that the template sheet relaxed the relational constraint from earlier stages. It should be noted that, although the number of constraint violation increased during problem-solving, the constraint violations were observed even in the first quarter. It means that the cue-readiness problem is involved, even when the template sheet was available.

Table 3: The percentages of segments violating the object-level and relational constraints.

	1/4	2/4	3/4	4/4
Object-level constraint (%)	6	19	13	46
Relational constraint (%)	40	41	47	47

Rating As in the previous experiment, we first examined the assumption that 5-min subjects failed more often than 1-min subjects. The average numbers of segments was 50.7 in the 5-min condition and 7.6 in the 1-min condition ($t(11) = 10.15, p <. 001$).

The ratings of each condition were summarized in Table 4. Unlike Experiment 1, we obtained different patterns of ratings. A three-way ANOVA (object-level $\times$ relational constraint $\times$ before-rating time (1- or 5-min)) revealed a significant main effect of the relational constraint($F(1,14) = 41.12, p <. 001$) and interaction between the relational constraint and the time before the rating ($F(1,14) = 10.06, p <. 01$). Although subjects in both conditions gave high rating scores for stimuli that violated the relational constraint, the 5-min subjects gave the highest score for stimuli violating both constraints, whereas the 1-min subjects did so for the stimuli violating only the relational constraint.

Table 4: Mean rating score.

	R–O–	R–O+	R+O–	R+O+
1-min	2.54	2.42	4.38	2.88
5-min	2.58	3	4.04	5.46

General Discussion

In this paper, We propose the dynamic constraint relaxation theory to investigate mechanisms underlying the cue-readiness in insight problem-solving. Our theory assumes that initial impasses are caused by the object-level and relational constraints and that these constraints are gradually relaxed by failures detected by the goal constraint. If our theory is correct, two predictions can be made. First, constraint violations increase during problem-solving processes, because constraints are more relaxed by facing more failures. Second, for the same reason, sudden noticing of crucial information is more likely observed in problem-solvers with more failures than those with fewer. If so, the ratings for constraint-violating stimuli should be different between them.

In order to examine these predictions, we conducted two experiments, using the T puzzle. Subjects' tasks were to solve the puzzle and to rate the closeness of various types of stimulus to the shape of "T." However, we could not obtain any supporting results in Experiment 1. The frequencies of constraint violations did not increase during problem-solving, and the ratings were not statistically different between the 2- and 7-min conditions. However, we found confirming evidence in Experiment 2 where the goal constraint operated more effectively by the template sheet. Violation of the object-level constraint increased when problem-solving proceeded. Furthermore, the ratings of subjects with more failures were different from those with fewer failures in a predicted way.

These results suggest that cue-readiness is caused by constraint relaxation. Due to noticing failure, the probabilities of constraint violations increases during the problem-solving processes, which makes problem-solvers ready to utilize crucial information. Another implication for the problem is that constraint violation at a single level may not be sufficient for insight and it should be coupled with violation at another level.

It is interesting to contrast our theory with a similar view proposed by Knoblich et al. (1999). They have proposed that constraint relaxation and chunk decomposition play key roles in insight problem-solving. Using matchstick arithmetic problems, they found empirical evidence supporting their theory.

Although both theories admit the key roles of constraint relaxation, there are a number of differences between the two. First, constraints used by Knoblich and their colleagues are task-specific. For example, they listed constraints concerning values, operators, and tautology. These constraints are specific to matchstick arithmetic problems, which makes it difficult for their theory to apply to a large number of insight problems that have no numerical values, mathematical operators, or equal sign.

Second, their theory is not dynamic in the sense that they do not assume any interactions with external environment. In their experiment, subjects were required to *mentally* transform various equations to desired states, which prohibits feedback from the external environment. As Seifert et al. (1995) properly claimed, we obtain information important for modifying our internal states as well as achieving the goal. Therefore, their theory of insight cannot explain findings in the present study, such as the time-course differences of the frequencies of constraint-violation and in the rating patterns observed in Experiment 2.

Third, related to the second, their theory cannot deal with the issue of what relaxes the constraints. They predicted the ease of relaxation based on the notion of the scope of constraints. However, what triggers constraint relaxation remains unanswered. In addition, the scope of the constraint cannot give a principled explanation for the relaxation patterns of the constraints. According to their theory, the relational constraint in our study has wider scope than the object-level one, because the former binds more than one element whereas the latter binds a single element. Thus, their theory predicts that the object-level constraint is more easily relaxed than the relational one. However, we obtained the opposite patterns of relaxation in Experiment 2.

To summarize, we agree that constraints forms an impasse and that insight is achieved by constraint relaxation, but oppose their notion of purely "cognitive" insight as well as task-specificity of constraints.

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