Exploring the Unconscious Nature of Insight
Using Continuous Flash Suppression and a Dual Task

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Abstract

A growing body of evidence suggests that implicit information processing has considerable effects on the higher-order cognitive processes such as insight problem solving. Is such implicit information stored within the working memory system, or is it processed in a storage system other than working memory? To differentiate these two possibilities, the present study examined solution of the T-puzzle, an insight problem, after participants were or were not subliminally presented with the hint images by using the continuous flash suppression (CFS). A spatial tapping task, which is deemed to interfere with spatial working memory, was introduced during CFS. The two hypotheses each predicted deteriorated and maintained performance on the T-puzzle after the tapping task. Contrary to these hypotheses, participants tended to exhibit better solution performance and relaxation of constraints after having the tapping task, either with or without subliminal presentation of the hints. Mechanisms by which the secondary task may facilitate insight problem solving are discussed.

Keywords: insight problem solving; working memory; implicit processing; T-puzzle; continuous flash suppression.

Introduction

Whereas explicit information processing is generally assumed to govern human higher thoughts, studies on implicit learning and memory have suggested that implicit information has considerable influence on our thoughts and behavior (Eagleman, 2011). For example, researchers have long assumed that conscious information processing including goal setting, planning, monitoring of actions, etc. plays a dominant role in human problem solving. However, a number of recent reports suggest that subliminally presented hint stimuli significantly facilitate subsequent performance on insight problems (Hattori et al., 2013; Suzuki & Fukuda, 2013). That is, information that is processed at the subconscious level may considerably influence higher-order cognitive processes such as insight.

Dynamic Constraint Relaxation Theory of Insight

Insight problem solving has several unique characteristics. First, whereas problems typically used in psychological experiments are simple, it is quite difficult for solvers to attain solutions by themselves (Ohlsson, 1992). Second, solvers stick to the incorrect approaches and make the same errors repeatedly (Kaplan & Simon, 1990). During these impasses, they frequently ignore useful information that was accidentally found or generated (Suzuki et al., 2000). Finally, insight seems to come to the mind suddenly.

A number of theories have proposed different mechanisms by which problem solving by insight is attained. We here adopt the ideas of the dynamic constraint relaxation theory (Suzuki, 2009), which has been developed under the strong influence of the notion of constraint (Knoblich et al., 1999) and Q-learning with softmax algorithm (Bridle, 1990). The theory assumes three kinds of constraints and a relaxation mechanism. The term "constraint" here refers to humans' natural tendencies to select appropriate options and exclude inappropriate ones out of the huge amount of information. The *object-level constraint* reflects people's natural preferences of how given objects are encoded. The *relational constraint* refers to solvers' natural preferences of how given multiple objects are related to each other. The *goal constraint* evaluates a match between the current and the desired states, and gives feedback to the constraints responsible for generating the current states. At the initial stages of problem solving, the object-level and relational constraints jointly operate to lead solvers to an impasse. However, as solvers repeat manipulations, feedback provided by the goal constraint dynamically alters the strength values of the object-level and relational constraints. This increases the probabilities of constraint violation. At a certain stage of problem solving, solvers accidentally violate each constraint to attain correct solution. This theory

effectively explains sudden nature of insight, effects of hints, individual differences, etc., and can apply to various insight problems (Suzuki, 2009; Suzuki et al., 2000).

The T-puzzle is a task that consists of four polygonal shapes that have to be put together to form a capital T (Figure 1). Despite the apparent simplicity of the task, it is actually a quite difficult problem, with less than 10% of naïve solvers attaining correct solution within 15 minutes (Suzuki et al, 2000). The T-puzzle has a number of characteristics unique to insight problems. First, most participants persist in placing the pentagon in a position either horizontal or vertical to the reference line. They also incorrectly try to fill the concave corner of the pentagon with the other pieces of shapes. Second, discontinuity of behavior is observed. That is, when insight occurs, the aforementioned incorrect manipulations are taken over by tilting the pentagon without filling its concave corner. Third, there are cases in which useful strategies that are generated are abandoned during impasses (Suzuki et al., 2000).
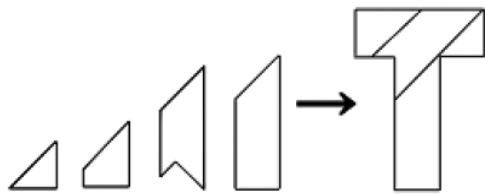

Figure 1: The T-puzzle: The four pieces and the solution.

From the perspective of the dynamic constraint relaxation theory, the object-level constraint in the T-puzzle relates to how each piece of shape is placed. Whereas there exist countless ways of putting each shape, people are strongly inclined to place it in a stable position, that is, either horizontally or vertically to the reference line such as the sides of the table. This makes it difficult for solvers to place the pentagon in a diagonal orientation. The relational constraint is considered to be how more than one piece of shape is connected to each other. People naturally tend to make a good-looking shape having fewer convex corners, which explains why solvers frequently fill the concave corner of the pentagon with the other pieces.

Working Memory System and Insight

Traditional models of working memory involving phonological loop, visuo-spatial sketchpad, and central executive have assumed that the working memory system stores information to which the agent is intentionally paying attention with conscious awareness (Baddeley, 1986). In contrast with these views, Hassin et al. (2009) proposed that working memory can operate unintentionally and without conscious awareness, and that the models of working memory should be expanded to implicit working memory.

In these research contexts, Suzuki and Fukuda (2013) used the T-puzzle to examine whether and how hint stimuli that are subliminally presented may influence subsequent insight problem solving. They used continuous flash

suppression (CFS), a technique that is frequently used to control conscious awareness of visual stimuli (Tsuchiya & Koch, 2005). In CFS, one eye is presented with a series of rapidly changing stimuli while the other eye is presented with a static visual stimulus. The static stimulus then becomes consciously repressed by the changing stimuli. Unlike the previous studies that put the hint stimuli in between the continuously presented frames of the moving images (Hattori et al., 2013), the CFS is advantageous in that it allows for subliminal presentation of the stimuli for several seconds or even longer. Suzuki and Fukuda (2013) found that participants who had been subliminally presented with the solution of the puzzle solved the problem in 55.7 seconds on average, significantly shorter than those who had had no prior presentation of the solution (311 seconds on average). Participants presented with subliminal hints also tended to show greater relaxation of constraints as they made more manipulations during problem solving. These data clearly suggest the influence of unconsciously processed information on the solution of an insight problem.

These results provide us with a new possibility concerning the nature of working memory. Since information used in the problem solving is assumed to be located in working memory, subliminally presented hint information should be stored in working memory, and exert control over the problem solving process. However, traditional models of working memory may not accept this interpretation because they assume that information in this storage is consciously accessible.

There are two plausible hypotheses to resolve the conflict between the experimental findings and the working memory theory. The first is the possibility that the there exists a place within the working memory system that the conscious processes fail to access. According to this view, subliminal hints of an insight problem would have been stored in this place to facilitate problem solving at the expsense of its capacity. The second hypothesis assumes that outside the working memory system there exists another storage, i.e., implicit working memory that is inaccessible by conscious process. In this view, subliminal information stored in this working memory would have enhanced subsequent problem solving without any load on the traditional working memory .

Purpose of the Study

Accordingly, the present study was designed to differentiate the two hypotheses described above. Working memory is considered to have limited capacity (Baddeley, 1986). That is, it is difficult to store and process too much information at a time. It would thus be possible to differentiate the aforementioned two hypotheses by introducing a secondary task that places loads on working memory during subliminal presentation of the hints. If the influence of subliminal hints on problem solving decreases by introducing the secondary task, that would support the first hypothesis that there is a place within working memory that refuses access by conscious processes. By contrast, if the secondary task has

no effects on the influence of subliminal hints, the second hypothesis would be supported that the subliminal information exists in the implicit working memory system. Even if neither of these hypothesis are supported, it could still be possible that the secondary task has positive/negative effects on the solution of the puzzle. In these cases, relationships between working memory and insight would be suggested. We subliminally presented the solution of the T-puzzle by using CFS before participants were actually confronted with the problem. We also introduced the spatial tapping task during CFS, which is considered to interfere with spatial working memory (Suto, 2005).

Method

Participants

Fifty-nine Japanese university students (28 females; mean age = 20.9 years) having normal or corrected-to-normal vision participated. Participants were assigned to the following four groups: *hint-tapping*, *hint-no-tapping*, *no-hint-tapping*, and *no-hint-no-tapping*, according to whether they were exposed to the subliminal hint and the tapping task during CFS. Thirteen were excluded because they reported experience with the T-puzzle prior to the study. Number of participants included in the analysis for each group was 14, 15, 9, and 8, respectively. The Ethics Committee of Aoyama Gakuin University approved the study. All participants provided written informed consent upon agreement to cooperate.

Settings and Stimuli

During subliminal presentation of the hint, a personal computer (iMac A1207, Apple, CA; CPU: Core2Duo 2.33 GHz) with a 20-inches LCD monitor was located on a table in front of the participant, who sat on a chair. A stereoscope for creating binocular rivalry (TKK 129, Takei Scientific Instruments, Niigata, Japan) was located adjacent to the participant's eyes. The stereoscope had a square-shaped opening window and two mirrors on each eye's side, so that different images could be presented to each eye at a time. The participant could look into the windows by putting his/her chin on the chin support. The rapid changing stimuli and a static image could appear simultaneously on each half of the display (right or left).
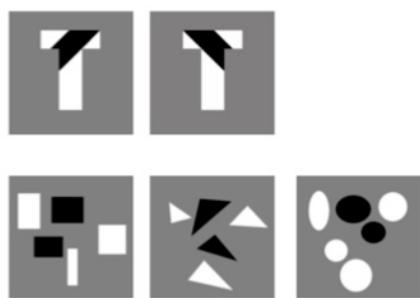

Figure 2: The hint (above) and test (below) stimuli.

On the side of the dominant eye, multiple geometrical figures with high contrast appeared at randomized locations (30 flips per second). Whereas images presented to the non-dominant eye (hereinafter referred to as "target stimuli") were sufficiently visible with one eye, these images were suppressed from visual awareness by the flash images. Three types of target stimuli were used for each stage of the experiment: an *instruction stimulus*, *test stimuli*, and *hint stimuli* (Figure 2). The instruction stimulus was an illustration of the face of Anpanman, a character of a popular Japanese anime, which was used to explain CFS to the participants. The test stimuli had three variations each consisting of multiple geometrical figures. These stimuli were used to confirm that participants did not consciously perceive the target stimuli during CFS. The hint stimuli were the correct solutions of the T-puzzle. There were two variations according to whether the concave corner of the pentagon was on the right or left side of the T-shape. Each of these variations was used randomly and equally often. The size of these target stimuli were between 5 and 7 degrees in visual angle. Brightness of these target stimuli was sufficiently decreased so that they would be invisible during CFS.

During subsequent solution of the T-puzzle, four pieces of wood that were components of the puzzle were placed on a table other than that during CFS. A sheet of paper provided a lattice of 4 x 3 squares (about 16 x 12 cm), which served as the outer frame when putting the wood pieces to form a T-shape. A digital camcorder (HDR-XR520V, SONY, Tokyo, Japan) was placed on a tripod behind the participant and the chair, in order to record manipulation of the wood pieces during solution of the puzzle.

Procedure

Dominant Eye Assessment The study took place in a quiet room arranged for psychological experiments. The experimenter (KT) first told the participant that the study consisted of two independent experiments each concerning visual perception and problem solving. The dominant eye of the participant was then assessed. The participant extended both arms, brought both hands together to create a triangular opening, then with both eyes open looked at a distant objet (a magnet) through the opening. The participant then alternated closing eyes to determine which eye is viewing the object (i.e., the dominant eye).

Presentation of Subliminal Hints The participant was next instructed to sit on the chair to look at the visual stimuli using CFS. The experiment room was made dim during presentation of stimuli by turning off the light. A small red fixation cross was then presented to each eye. If necessary, the participant adjusted the angles of the mirrors equipped in the stereoscope and the heights of the chair and the chin support, until the two crosses appeared to be in the same spatial location at the center of the window.

Then the experimenter explained CFS to the participant. The instruction stimulus was presented to the non-dominant eye. After confirming that the participant failed to perceive the instruction stimulus, the experimenter told the participant to close the dominant eye so that s/he would see the instruction stimulus. The participant was then told that the instruction stimulus presented to the non-dominant eye was suppressed by the flash images presented to the dominant eye. The participant was also told that this experiment on visual perception aims to change the brightness of the stimulus presented to the non-dominant eye in order to determine the extent to which that stimulus is perceived. The flash and the instruction stimuli lasted for 10 seconds for this and the subsequent test stages.

For the two conditions that involved the spatial tapping task (i.e., hint-tapping, and no-hint-tapping), a white square appeared at one of the three locations, i.e., right, center, or left, within the flash images presented to the dominant eye. Following practice, the participant was told to press the corresponding key on the keyboard according to the location of the white square during CFS. The square successively appeared at random locations during the period, to which the participant had to respond as quickly and accurately as possible. The tapping task was absent in the other two conditions (i.e., hint-no-tapping, and no-hint-no-tapping).

Next, one of the randomly selected test stimuli was presented to the non-dominant eye. The participant was required to verbally report if s/he perceived any visual stimuli other than the flash images. The actual purpose of this test stage was to confirm that the participant did not perceive the stimulus presented to the non-dominant eye. This confirmation was made twice, and participants who reported that s/he perceived the test stimuli were assigned to the conditions with no subliminal hint presentation (i.e., no-hint-tapping or no-hint-no-tapping). Then, for conditions with subliminal hint (i.e., hint-tapping and hint-no-tapping), one of the hint stimuli were presented to the non-dominant eye. This hint presentation was conducted using instructions and procedure identical to those during test stimuli, so that the experimenter could confirm that the participant did not perceive the hint. For conditions with no subliminal hint (i.e., no-hint-tapping and no-hint-no-tapping), one of the test stimuli was presented in the same way as in the previous stage. The participant was then told that the first experiment had finished.

Solution of the T-puzzle The participant was then instructed to sit on another chair in the same experiment room for the second experiment on problem solving. The task here was to actually solve the T-puzzle. The participant was told to put together the four pieces of wood place on the table to form a T-shape. The participant solved the task on the sheet of paper having the lattice as the outer frame, which was expected to moderately facilitate insight. When correct solution was not attained within 15 minutes, the participant was verbally advised that s/he should not fill the concave corner of the pentagon with the other pieces. When

the participant failed to solve the puzzle three minutes after this advice (18 minutes in total), the solution phase was terminated and the correct solution was shown. Throughout the solution period, the digital camcorder recorded the manipulation of the wood pieces, though not the face of the participant. Posture of the participant was corrected if his/her own body parts obstructed the recording. All participants were debriefed after completing the study.

Results

Accuracy and Solution Time

Table 1 shows proportions of participants who successfully solved the puzzle－for those without advice (solution within 15 minutes) and for those either with or without advice (solution within 18 minutes). Participants reporting prior experience with successful solution of the puzzle are not included. Even though proportions of correct solution were generally lower than those in Suzuki and Fukuda (2013), more than 33 % of participants in the hint-tapping and the no-hint-tapping conditions successfully solved the puzzle without advice, in contrast to those in the remaining two conditions (20 % or less). Compared with the control (no-hint-no-tapping) condition, frequency of participants for the other three conditions with successful solution failed to differ significantly, either when solvers without advice (Fisher's exact test; all $ps > 0.254$) are considered or when those with advice are included (all $ps > 0.329$). However, whereas successful solvers without advice were significantly less frequent than non-successful ones for the hint-no-tapping (1/2 binomial test; $p = 0.018$) and the no-hint-no-tapping ($p = 0.035$) conditions, these were not the cases for the hint-tapping ($p = 0.212$) or no-hint-tapping ($p = 0.254$) conditions. These data show trends that participants who had been exposed to the tapping task during CFS were better at solving the subsequent insight problem than those who had not.

Table 1: Proportions of solvers for each condition.

Condition	N total	% solvers (no advice)	% solvers (advice)
Hint-tapping	14	35.7	57.1
Hint-no-tapping	15	20.0	46.7
No-hint-tapping	9	33.3	33.3
No-hint-no-tapping	8	12.5	37.5

Table 2: Mean (SD) solution time in seconds.

Condition	Solution time (no advice)	Solution time (advice)
Hint-tapping	347.7 (164.3)	608.8 (361.4)
Hint-no-tapping	518.1 (290.4)	777.6 (295.3)
No-hint-tapping	468.4 (189.1)	468.4 (189.1)
No-hint-no-tapping	581.1 (0.0)	809.7 (161.9)

Table 2 shows mean solution time for the successful solvers. Participants who failed to solve the puzzle were not included in this analysis. Without advice, only one participant solved the puzzle for the control (no-hint-no-tapping) condition. Nevertheless, solution time tended to be shorter in the conditions with tapping than in those without tapping, parallel to the trends observed for the frequency of participants. When directly compared with the solution time for the successful solver in the control condition (581.1 seconds), mean solution time for the hint-tapping condition was significantly shorter (one-sample t-test: $t[4] = -2.842$, $p = 0.047$), although those for the hint-no-tapping ($t[2] = -0.307$, $p = 0.788$) or no-hint-tapping conditions ($t[2] = -0.843$, $p = 0.488$) were not. The trend was consistent when the successful solvers after taking advice were included.

Relaxation of Constraints

A further analysis was conducted in association with the dynamic constraint relaxation theory. As mentioned above, solving the T-puzzle requires violation of both the object-level and the relational constraints (Suzuki, 2009). Videotaped data were used to count the numbers of segments in which violation of these constraints occurred. A "segment" in this context was deemed to start when one piece of the puzzle was connected to another piece and to end when these pieces were separated. Violation of the object-level constraint refers to the cases in which a piece is placed in a diagonal orientation, and violation of the relational constraint refers to the cases in which the pentagon is connected to another piece with its concave corner left unfilled. Both successful and non-successful solvers were included in this analysis. To elucidate the temporal course of the violation of constraints, the total number of segments for each constraint and condition was divided into quarters. Figure 2 depicts mean proportions of violation for each condition and quarter of segments (Q1 to Q4). A four-way repeated-measures analysis of variance (ANOVA) with hint/no-hint (2), tapping/no-tapping (2), and success/non-success (with no advice) (2) as between-subject factors and quarter of segments (4) as a within-subject factor was conducted for each constraint. The proportions were arcsine transformed in order to make distributions more normal for parametric statistics.

For the object-level constraint, main effect of tapping ($F[1, 38] = 5.000$, $p = 0.031$), main effect of success ($F[1, 38] = 4.433$, $p = 0.042$), main effect of quarter ($F[3, 114] = 15.842$, $p < 0.001$), and interaction between success and quarter ($F[3, 114] = 7.114$, $p < 0.001$) were statistically significant. Multiple comparisons with Bonferroni correction showed that violations were more frequent in Q4 than in Q1, Q2, and Q3 (all $ps < 0.001$). In these data, participants who were exposed to the tapping task showed more frequent violation of the constraint than those who were not. In addition, successful solvers exhibit more frequent violations than non-successful ones, with these violations becoming more frequent towards the later stages of problem solving. These trends were generally consistent

for the relational constraint. Main effect of tapping ($F[1, 38] = 3.489$, $p = 0.070$) and main effect of success ($F[1, 38] = 3.755$, $p = 0.060$) approached statistical significance, and main effect of quarter ($F[3, 114] = 20.545$, $p < 0.001$) was statistically significant. Multiple comparisons with Bonferroni correction revealed significant differences between Q4 and Q1 ($p < 0.001$), Q4 and Q2 ($p < 0.001$), Q4 and Q3 ($p = 0.001$), and between Q3 and Q1 ($p = 0.015$). Other than these outcomes, there were no statistically significant main effects or interactions for these constraints.
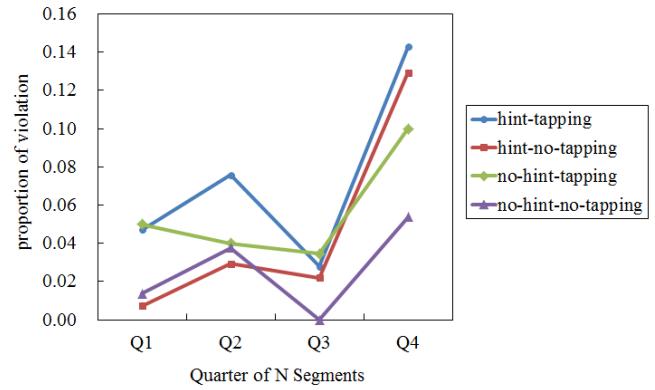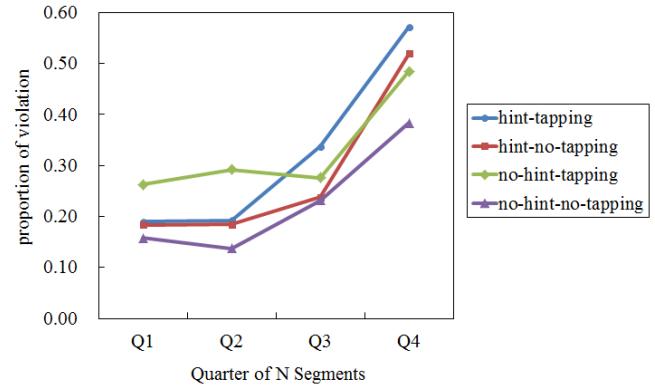

Figure 3: Temporal course of constraint relaxation

Discussion

Our initial hypotheses predicted enhanced performance on the T-puzzle with the subliminal hint presentation. They also predicted either deteriorated or maintained performance on the puzzle with the introduction of the spatial tapping task during CFS. The results supported neither of these possibilities. Instead, participants who had been exposed to the tapping task tended to show more frequent and quicker solution of the problem. These trends were consistent when manipulations of the pieces were analyzed from the perspective of the dynamic constraint relaxation theory. Participants having the tapping task tended to exhibit greater relaxation of the constraints than those having no secondary

task. Thus, contrary to our expectations, engaging in a secondary task during CFS, rather than the hint itself, seems to have facilitated insight. Additional findings were that successful solvers tended to show more frequent violation of constraints, and that proportions of violations were higher toward later stages of solution.

Nevertheless, the present results should provide us with another view regarding relationships between insight and working memory system. One possible scenario may be that engaging in a task that loads one subsystem of working memory (i.e., visuo-spatial sketchpad) activates general executive mechanisms involved in working memory, and that activation later facilitated violation of constraints when solving a spatial insight problem. This may suggest that working memory system and insight are positively associated with each other, at least when these mechanisms are successively activated in this order. These interpretations appear consistent with DeCaro et al. (2008) showing that people having lower working memory capacity learned a procedural/unconscious task faster than those having higher working memory capacity. These data suggested that explicit testing of the hypothesis without working memory load may inhibit implicit learning, which seems consistent with the idea that working memory load can relax constraints. Even though DeCaro et al. used a category learning task instead of an insight problem, it may be plausible that similar processes were involved in the present study as well.

These interpretations would still require cautious considerations. First, rather than the secondary tapping task, the primary visual task used during CFS may have significantly interfered with the storage of the hint information (e.g., Miyake & Shah, 1990). The detailed nature of the geometrical stimuli used to create CFS may also explain why the positive effect of the hint found in the previous study (Suzuki & Fukuda, 2013) was not replicated in the present experiment. These need to be explored by varying the nature of the visual stimuli. Second, it may be plausible that the tapping have presented a dual-task challenge to the participants, thereby encouraging them to try harder to perform better during the solution period. It seems desirable to control such motivational factors by introducing different types of secondary tasks. In addition, because participants in the present study who perceived the test stimuli were systematically assigned to the conditions with no hint, it should be required to address the potential relations between how the solver perceives the implicit stimulus and how strongly the hint facilitates the solution. These further modifications should help to elucidate the mechanisms by which implicit processing and working memory may influence insight problem solving.

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