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Effect of Positive and Negative Instances on Rule Discovery: Investigation Using Eye Tracking

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Abstract

This study investigates how participants reject an initial rule when they face positive and negative instances of an initial rule. Using eye movement data, we analyzed a perspective that indicated the type of rules that participants consider. The results show that, only in negative instances, participants considered rules from the perspective that they used for finding and confirming the initial rule. We concluded that, when participants face negative instances, they tried to change the initial rule peripherally to explain them. This appeared in the form of a longer consideration from an initial perspective in negative instances.

Keywords: Rule discovery; eye tracking; anomalous data; attentional learning; perspective

Introduction

Finding regularities is one of the most important activities not only in science but also in many aspects of daily life. People can find regularities in their daily experiences or observed data and use them for predictions and decision making. However, if a rule that they find at first (i.e., an initial rule) is incorrect, they need to reject it on the basis of their observed data and start considering a new one. We focus on such a situation, specifically one in which people face negative evidence to the initial rule. In particular, we investigate the period in which both positive and negative instances appear.

The process of finding and rejecting the initial rule consists of the following three phases. The first phase is the "initial phase" in which participants find and use the initial rule. In this phase, participants always observe positive instances. Our study focuses on the second phase called the "transition phase." In this phase, participants face both positive and negative instances. The third phase, the "post-transition phase," follows the transition phase, and it includes the time in which participants try to find a rule that is valid for all instances. Almost all instances in this phase are negative to the initial rule; hence, the initial rule is absolutely rejected.

Perspective and Eye Tracking

Using a relatively easy rule discovery task, such as Wason's 2-4-6 task, many researchers have shown that disconfirmation is effective to reject the initial rule (e.g., Wason, 1960). They obtained these results from analyses based on the best guess regarding the rule collected by verbal or written reports. However, this method does not reveal thoughts before participants reveal their best guess. This period contains many "unexpressed thoughts" that cannot be reflected in the best guess, such as thoughts that are abandoned before they become obvious rules or that do not yet reach obvious rules. Compared with other phases, it is difficult to make one's thoughts into the form of a rule in the transition phase; therefore, more unexpressed thoughts appear during this phase. Although unexpressed thoughts are crucial information regarding the process in the transition phase, a traditional analysis of verbal reports of the rule has difficulty in interpreting them because they do not take the form of a rule.

We use the following two new approaches to investigate unexpressed thoughts: the analysis of "perspective" and "eye tracking." The perspective constrains the type of rules that people consider. There are an incredible number of available rules; therefore, participants cannot simultaneously consider all rules. By deciding upon the perspective, participants consider only rules matching their perspective, which makes them able to consider an adequate number of rules. The perspective includes the function or role of rules and the factor used for rules. For example, Klahr and Dunbar (1988) represented hypotheses as frames and clustered them on the basis of the role of frames in scientific reasoning. Participants in their experiment considered the hypotheses in a cluster that had an identical role in their mind. The information provided by the analysis of the perspective about the unexpressed thoughts in the transition phase is more useful than that provided by the analysis of the reported best guess.

Lien and Lin (2011) investigated the effects of perspective on rule discovery performance using Wason's 2-4-6 task. They found that participants who could discover the rule changed their perspective more frequently than those who could not. However, they analyzed only the reported rules, which have a problem as mentioned above. Haverty, Koedinger, Klahr, and Alibali (2000) showed that the crucial factor for rule discovery was the ability to judge which type of rules participants should pursue, that is, which perspective they should use. The protocol analysis used in their study has been used in many preceding studies on rule discovery. Although it provides a detailed process of rule discovery, it still has two problems for the purpose of this study.

The first problem is that participants mention only their conscious thoughts. The verbal protocol cannot always capture unexpressed thoughts because participants are not always conscious of them. The second problem is that protocol data is coarse-grained on the time scale. In general, the speed of thinking is faster and more fluent than that of verbalization. In the transition phase, short thoughts that come and go in the mind appear frequently. Such short thoughts are difficult to put into words. For these reasons, we use eye tracking, which continuously gives more fine-grained data. Recently, eye movement data has been utilized in many studies, such as

category learning and insight problem solving, and has produced good results (e.g., Knoblich, Ohlsson, & Raney, 2001; Rehder & Hoffman, 2005).

Hypotheses

We define a perspective needed to find an initial rule as an "initial perspective." The hypotheses in this study are as follows. First, in the initial phase, participants mainly consider rules from the initial perspective. The preceding studies on category learning showed that once participants learned a rule, they focused only on the relevant features and ignored irrelevant features (e.g., Rehder & Hoffman, 2005). Similarly, once participants found a valid rule (i.e., an initial rule), they focused only on the relevant perspective (i.e., the initial perspective) and ignored irrelevant perspectives.

The transition phase has the following two hypotheses: the "shift hypothesis" and "retain hypothesis." In the shift hypothesis, we predict that participants will shift their focus from the initial perspective to other perspectives as soon as they face only one negative instance. According to Popper, a hypothesis can be normatively falsified by just one negative instance. Using Wason's 2-4-6 task, many studies have shown that one disconfirmation is enough to reject the initial rule. If the shift hypothesis is supported, participants will consider rules from the initial perspective to be the same as or shorter than those from other perspectives in the transition phase. The second retain hypothesis suggests that focus on the initial perspective will be retained. In this case, participants will continue to consider rules from the initial perspective rather than those from other perspectives in the transition phase.

There are two possible explanations for retaining consideration from the initial perspective. First, participants use the initial perspective for peripheral changes of the initial rule in order to adapt it to negative instances; for example, to add an additional or exceptional rule. Chinn and Brewer (1993) showed that participants were likely to hold onto their theories by reinterpreting data, using the peripheral theory change, and so on. In addition, Dunbar (1995) demonstrated that participants did not often change their hypotheses even if they faced inconsistent evidence. The second explanation is based on attentional learning. The attentional learning model (e.g., EXIT; Kruschke, 2003) explains eye movement data in category learning according to the following process. First, participants learn the relevant features that should be focused on and irrelevant features that should be ignored. Positive feedback to their learned rule reinforces their focus on the learned features. On the other hand, if they face negative feedback, they shift their focus from the learned relevant features to other features. On the basis of this model, the participants in this study would also shift their focus from the learned initial perspective to other perspectives when they face negative instances. In contrast, when they face positive instances, they again focus on the initial perspective; as a result, consideration from the initial perspective is observed.

We can judge which explanation is accepted from how participants consider rules in each negative and positive instance. If the "peripheral change" explanation is accepted, participants consider rules from the initial perspective when they face negative rather than positive instances. The initial rule is not valid in negative instances; therefore, participants need to consider modified rules from the initial perspective to improve the initial rule. On the other hand, when participants observe positive instances in which the initial rule is valid, they do not need much consideration from the initial perspective. If the "attentional learning" explanation is accepted, participants consider rules from the initial perspective when they face positive rather than negative instances. Observing positive instances reinforces the focus on the initial perspective because the initial rule is valid in these instances. On the other hand, negative instances shift participant's focus from the initial perspective to other perspectives.

Task

We created a new rule discovery task in which a fixation area and perspective correspond. Figure 1 shows an example screenshot of the task display corresponding to one instance. One instance consists of three panels (arrow, compass, and number) and eight letters (a-h) in the center of the display. These eight letters were arranged in a circle with letter *a* taking the 12 o'clock position. One of these letters was displayed in each instance (we call it the "target letter"). Participants were asked to find a rule determining which panel related to the target letter and how the objects in the related panel determined it through observations of some instances. We told them in advance that only one of the three panels was related to the target letter and that the other two panels had no relationship.

We gave a different function to each of the three panels. In the number panel, two numbers from 1 to 4 were displayed. Each number indicated the order of each letter, such as 1 was *a* and 2 was *b*. In the arrow panel, two circular arrows from 45, 90, 135, and 180° were displayed. The angle of each arrow indicated the degree of a rotation from the starting letter

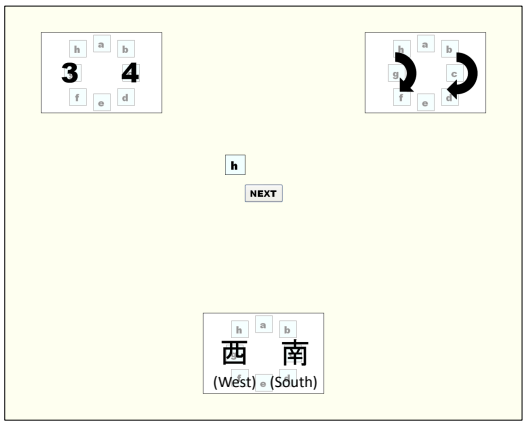

Figure 1: Example screenshot of the task display used in this study.

to certain letter. For instance, if the participant set a as a starting point, a 45° arrow indicated b and a 90° arrow indicated c. In the compass panel, two directions from north, east, south, and west were displayed in Chinese characters. Each direction of the compass panel indicated the direction on a map, that is, north was the upper one (a) and south was the lower one (e). The objects within each panel were allowed to be combined. Each panel with a different function corresponded to a different perspective; therefore, the observation times of each panel corresponded to the amount of investigation from each perspective.

We prepared two rules that determined the relationship between the target letter and panel. One was the "initial rule" discovered in the initial phase. In this rule, the target letter is the letter moved from a by a sum of the angles of two arrows on the arrow panel. For example, when the arrows are at 135 and 180° (Figure 1), the target letter h is identified by moving from a (at 12 O'clock) by the sum of the two arrows' angles ($135 + 180 = 315°$). The other rule is the "target rule" that is valid throughout the task. In this rule, the target letter is the letter in the opposite (replace north with south) position to the position of the letter indicated by a combination of two directions on the compass panel. For example, with west and south directions (Figure 1), the target letter h's position was indicated by combining two directions (west and south = south-west) and then replacing south with north (north-west). The initial perspective needed to find the initial rule was the arrow perspective, and the target perspective needed to find the target rule was the compass perspective.

The task consisted of eleven blocks. A block consisted of five observations of an instance and four tests. In an observation, participants considered rules by observing such an instance, as exemplified in Figure 1. By clicking on the NEXT button or after a certain number of seconds, the next instance was presented. Participants were not permitted to return to prior instances. After observing five instances, participants announced the rule which they found and then started the test. In the test display, three panels and the buttons of each of the eight letters were presented. Participants predicted the target letter and selected the button of the letter. The next problem was presented by clicking on the button or after 15 sec. Four problems were conducted in total.

We separated eleven blocks into the following three phases: the first four blocks were the initial phase, the next three blocks were the transition phase, and the final four blocks were the post-transition phase. In the initial phase, only positive instances that supported both the initial and target rules were presented. All participants were expected to find the initial rule and focus on the initial perspective. In the transition phase, both the positive and negative instances to the initial rule are presented, whereas the target rule is valid in all these instances. In the post-transition phase, all instances were positive to the target rule and negative to the initial rule. In this phase, we expected that participants would try to find the target rule. All participants completed eleven blocks, even if they found the target rule.

Predictions

On the basis of our hypotheses, we made the following predictions. First, in the initial phase, the observation time of the arrow panel corresponding to the initial perspective would be longer than those of the other panels. In the transition phase, we expected different result for each hypothesis. If the shift hypothesis was approved, the difference of the observation time between the three panels would disappear. If the retain hypothesis was approved, the observation time of the arrow panel would be longer than those of the other panels. Furthermore, when the retain hypothesis was supported, there were two predictions based on the two explanations for observations of the difference. The prediction derived from the peripheral change explanation was that the tendency of the longer observation time of the arrow panel is more significant in negative instances than that in positive instances. On the other hand, if the attentional learning explanation is accepted, the tendency of the longer observation time of the arrow panel is more significant in positive instances than that in negative instances.

Experiment 1

Hereafter, when we mentioned the positive and negative instances, they were defined according to the initial rule. The primary purpose of Experiment 1 was to confirm that the initial rule was rejected progressively in the transition phase, as expected. For this purpose, we compared two types of conditions: one "divided" condition in which the transition phase was removed, and two "mixed" conditions in which the transition phase was conducted as explained in the task section. The second purpose was to investigate whether the more negative instances the participants were given, the faster they rejected the initial rule in the transition phase. For this purpose, we manipulated the ratio of negative instances in the transition phase in the two mixed conditions.

In the divided condition, to remove the transition phase, the post-transition phase followed immediately after the initial phase; namely, after the initial phase ended, all presented instances switched into negative. This manipulation was predicted to make participants reject the initial rule drastically after the initial phase because there was no transition phase in which both positive and negative instances were presented. On the other hand, in the two mixed conditions, the initial rule was rejected progressively in the transition phase. The two mixed conditions consisted of a "mixed-increase" condition in which the ratio of negative instances increased in the transition phase and a "mixed-few" condition in which one negative instance appeared in a block. If the ratio of negative instances affects the timing of rejecting the initial rule, the rejection in the mixed-few condition would occur slower than that in the mixed-increase condition.

Method

Participants Ninety undergraduates participated in Experiment 1. Each participant was assigned to one of the three conditions.

Task and Procedure We manipulated the amount of negative instances in blocks 5, 6, and 7. In the divided condition, only negative instances were presented after the second trial of block 5. The number of negative instances increased from one to three in the mixed-increase condition and was always one at each block in the mixed-few condition. Before the second trial in block 5, all instances were positive in all conditions. The maximum observation time of each instance was 35 sec.

The rule discovery task was conducted one at a time in a classroom. Each participant engaged in the task individually at his or her own pace using a computer terminal. Before starting the task, participants were instructed about the task and learned the functions of each panel through practice. Participants used a keyboard to describe the rule they found.

Results

Seven participants who did not follow the instructions were excluded from analyses. We categorized the reported rules in each block into the following three categories: the initial rule, the target rule, and others or none. In Experiment 1, we focused on the rejection of the initial rule; therefore, we analyzed the discoverer of the initial rule who described only the initial rule in blocks 3 and 4. Twenty-four non-discoverers were excluded from analyses. The data of 24 participants in the divided condition, 12 participants in the mixed-increase condition, and 22 participants in the mixed-few condition were used for analyses.

Figure 2 shows the ratio of participants in each condition whose reported rule was categorized in the initial rule in each block. As expected, in the divided condition, a drastic decline was observed in block 5. Only two participants (9.09%) stated the initial rule in block 5 and none stated it in blocks 6 and 7. The rejection of the initial rule was slower in the two mixed conditions than that in the divided condition. The ratio of participants who stated the initial rule in block 5 was high and nearly the same in the mixed-increase condition (91.66%) and mixed-few condition (86.36%). In block 6, this ratio was moderately lower in the mixed-increase condition (16.66%) than that in the mixed-few condition (31.81%). More than 15% of participants kept the initial rule in block 7 in both conditions.

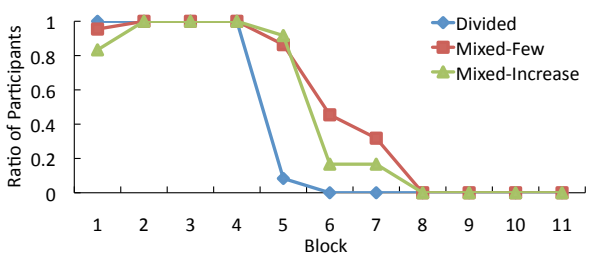

Figure 2: Ratio of participants in each condition whose reported rule was categorized in the initial rule in each block.

The same result was observed in the tests. The use of the initial rule to identify the target letter decreased more slowly in the two mixed conditions than that in the divided condition. The ratio of participants who stated the target rule started increasing in block 5 and reached around 50% in block 11. There was no difference in the three conditions.

Discussion

In the results of Experiment 1, we observed a drastic decline in the number of participants who identified the initial rule only in the divided condition. This means that, when only negative instances were presented after a certain point, the initial rule was rejected without taking any time to consider it. In contrast, we observed progressive declines in the two mixed conditions. These results support our prediction that, in the transition phase in which both positive and negative instances were presented, participants would reject the initial rule progressively, considering whether they should reject it. Participants in the mixed-few condition tended to reject the initial rule more slowly than those in the mixed-increase condition. This means that the more negative instances participants were given, the faster they rejected the initial rule. The results of Experiment 1 show the validity of our task.

Experiment 2

The purpose of Experiment 2 was to investigate how participants considered rules from each perspective in the transition phase using the task used in Experiment 1. Using eye movement data, we tested the two hypotheses: the shift and retain hypotheses.

Method

Participants Twenty undergraduates participated in Experiment 2.

Task and Apparatus We conducted the rule discovery task two times, identified as task 1 and task 2. Task 1 consisted of three blocks and had no rule, and the combinations of the objects on each panel and the target letter in the task were randomly created. The purpose of task 1 was to confirm that there was no inherent difference between the observation times of each panel. Task 2 had the same format as the mixed-increase condition in Experiment 1. The maximum observation time of each instance was 40 sec.

Participants' eye movements were recorded using a Tobii T60 eye tracker at 60 Hz. We presented the task display on a 17-in monitor with a resolution of 1280 $\times$ 1024 pixels. Participants were seated approximately 60 cm away from the monitor. The size of visual angle on the panels was approximately 7.57° $\times$ 5.05°.

Procedure Experiment 2 was conducted individually. First, participants were instructed about the task and learned the

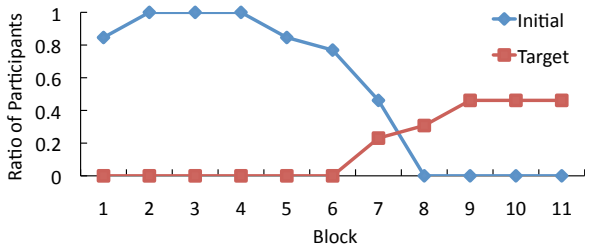

Figure 3: Ratio of participants who announced each rule.

functions of each panel through practice. Task 1 was conducted before task 2. Participants were asked to find the rule but were not instructed that there was no rule. The procedure for each task in Experiment 2 was the same as that in Experiment 1, except that the best guess of the rule was announced verbally. Before starting each block, a calibration for recording eye movement was performed. All eye movements throughout each task were recorded.

Results

Four participants who did not discover the initial rule were excluded from analyses. Two participants whose eye movement data were not recorded more than 50% of the time and one participant whose fixations on the lower panel were not recorded correctly were excluded from analyses.

Reported Rules Figure 3 shows the ratio of participants who announced the initial or target rule in each block. As observed in Experiment 1, the ratio of participants who announced the initial rule declined progressively from blocks 5 to 7. The ratio of participants who announced the target rule was also similar to that of Experiment 1: this number started increasing in block 5 before reaching 46.15% in block 11.

Eye Movement We calculated each participant's observation time of each panel. Then, we calculated the mean observation time of each panel in task 1, the initial phase, and the transition phase to investigate two hypotheses. We did not use the data in block 1 in which not all participants announced the initial rule for calculating the mean observation time in the initial phase. First, we conducted a one-way within subject ANOVA (panel: arrow, compass, and number) for the observation time in task 1 to confirm that there was no coherent difference between three panels. A significant main effect of the panel was not observed ($F(2,24) < 1$). This result means that the different contents of each panel or functions of rules did not affect observation time.

To investigate which hypothesis, the shift or retain hypothesis, was supported, we conducted a 2 (phase: initial and transition) $\times$ 3 (panel: arrow, compass, and number) within subject ANOVA for mean observation times (Figure 4). The main effect of the phase factor ($F(1,12) = 17.351, p = .001$) and the panel factor reached significance ($F(2,24) = 13.174, p < .001$). The interaction of the two factors was not significant ($F(2,24) < 1$). To confirm the difference in the observation times in each phase, we conducted a

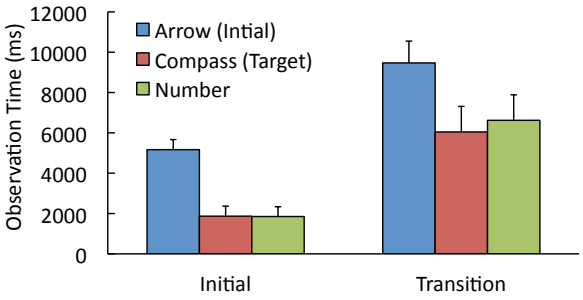

Figure 4: Mean observation time of each panel in each phase of the task 2 (bars show standard errors).

planed one-way within subject ANOVA (panel: arrow, compass, and number) for the observation times of each phase. In both the initial and transition phases, a significant main effect of the panel factor was observed (initial: $F(2,24) = 23.367, p < .001$; transition: $F(2,24) = 5.528, p = .011$). We observed the same tendency in both phases. The observation time of the arrow panel was significantly longer than those of the compass panel (initial: $p < .001$; transition: $p = .059$) and the number panel (initial: $p = .002$; transition: $p = .045$). There was no significant difference between the observation times of the compass and number panels (both phases: $ps = 1.000$). These results support the retain hypothesis that participants focused on the initial perspective; therefore, we continued the analyses to examine two explanations for the retain hypothesis.

We calculated the observation times for each positive and negative instance in all instances from the second trial in block 5 to the fifth trial in block 7, i.e., the transition phase (Figure 5). We conducted a 2 (instance: positive and negative) $\times$ 3 (panel: arrow, compass, and number) within subject ANOVA for the mean observation time. As a result, the interaction between the instance and panel factors reached significance ($F(2,24) = 5.489, p = .011$). The significant simple main effect of the panel factor was not observed in positive instances ($F(2,24) = 1.723, p = .200$). In contrast, in negative instances, the simple main effect of the panel factor was significant ($F(2,24) = 7.123, p = .007$). The observation time of the arrow panel was significantly longer than those of the compass panel marginally ($p = .067$) and the num-

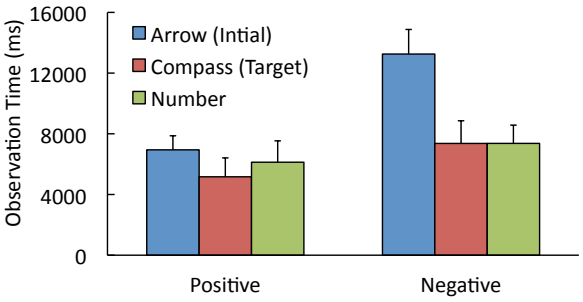

Figure 5: Mean observation time of each panel for each positive and negative instance in the transition phase (bars show standard errors).

ber panel ($p = .016$). There was no significant difference between the observation times of the compass and number panels ($p = 1.000$). The main effect of the instance factor ($F(1,12) = 57.298, p < .001$) and the panel factor reached significance ($F(2,24) = 6.139, p = .007$). The result that the participants considered rules from the initial perspective in negative instances rather than positive instances supports the peripheral change explanation.

Discussion

In Experiment 2, we tested two hypotheses using eye movement data. In the initial phase, the results were consistent with our prediction: the observation time of the arrow panel was longer than those of the other panels. This means that the investigation from the initial perspective was conducted more often than that from other perspectives. This tendency was retained in the transition phase. This supports the retain hypothesis that focus on the initial perspective is retained if participants face negative instances. The analysis comparing the observation times in each positive and negative instance reveals that, although participants considered the rules to the same extent from all perspectives in positive instances, they considered rules from the initial perspective longer than those from other perspectives in negative instances. These results suggest that retained focus on the initial perspective is because of an attempt to improve the initial rule from the initial perspective when negative instances are given.

General Discussion

In this study, we investigated the process of finding and rejecting an initial rule using eye movement data. We analyzed a perspective that indicated what types of rules participants considered. Our experiments yielded the following results: (1) In the initial phase in which only positive instances were given, participants focused on the initial perspective rather than other perspectives. (2) In the transition phase in which both positive and negative instances were given, participants retained a tendency to focus on the initial perspective. (3) The tendency to focus on the initial perspective was observed only when participants faced negative instances. On the basis of these results, we accept the retain hypothesis and the peripheral change explanation.

Participants' consideration of each rule from each perspective is out of the range of our study. We consider some possibilities about what participants were thinking from the initial perspective on the basis of the results of our experiments and the Chinn and Brewer's classifications (1993; Mason, 2001). The first possibility is that participants did not accept negative instances as valid, which corresponds to two of Chinn and Brewer's classifications: ignoring and rejecting. We can deny this possibility because we, as experimenters, guaranteed the validity of the instances. The second possibility is that participants did not try to explain negative instances, which corresponds with the categories of excluding and abeyance. If this possibility is true, the observation times of negative instances would be short; however, they were not. Furthermore, the participants' task was to explain all instances. The third possibility is that they reinterpreted negative instances, which is Chinn and Brewer's category of reinterpreting. This possibility is rejected because interpretations other than those we provided regarding how to use the objects on each panel were not allowed.

The last two Chinn and Brewer's classifications are peripheral change and theory change, which, in this study, correspond to a peripheral change of the initial rule and a consideration of a whole new rule, respectively. For the following three reasons, it is most likely that participants tried to change the initial rule peripherally. First, in both experiments, many participants announced the initial rule in the transition phase. Second, the observation times of negative instances were longer than those of positive instances. Finally, there is normatively no benefit to focus on the initial perspective if participants consider a whole new rule. When participants kept the initial rule in their minds, they did not require much investigation from the initial perspective in positive instances. Consequently, a difference in the observation times from each perspective was not observed.

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