An experimental study on the observation of facts in explanation reconstruction

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Abstract

Explanation reconstruction performs a crucial role not only in the progress of science but also in educational practices and daily activities, including the comprehension of phenomena. In this study, we conducted experiments to examine the factors that facilitate shifts in explanations. We focused on the transition of attention on a key fact that contradicts an initial explanation and has a central role in its reconstruction. We used a short story as an experimental material in which participants first constructed an initial explanation and then reconstructed it. In the experiment, we controlled the time of presentation of the key fact (bottom-up condition), reflective thinking (top-down condition), and the two together (bidirectional condition) to facilitate understanding of the explanatory shift. The experimental results are summarized as follows. First, when the prior explanation was rejected, attention to the key fact was inhibited although a new explanation was required. Second, the successful group increased their attention on the key fact just before the explanatory shift. Third, protection of the preceding explanation with unobserved facts was inhibited by guiding the participants ' attention toward the key fact. Finally, although the initial explanation was not completely shifted, a explanatory pre-shift was achieved by activating reflective thinking with attention to the key fact.

Keywords: eye-movement analysis; explanation reconstruction; explanatory shift; reinterpretation

Introduction

Scientific activities aim to understand the world in two ways: descriptive and explanative (Simon, 2000). Descriptive understanding describes the nature and characteristics of phenomena by observations and experiments, whereas explanative understanding reveals the mechanisms behind the phenomena and the reasons why such phenomena occur.

Through the history of science, first descriptive understanding is usually established and then explanative understanding is investigated.

On the basis of historical facts, we can confirm many cases where the explanation for a certain phenomenon was completely changed because the structures of the explanation and the concepts of objects were essentially shifted. Such cases are generally observed in the history of science, e.g., the shift from the caloric theory to the oxygen theory and the transition from Newton's traditional theory to Einstein's relative theory(S. F. Mason, 1953).

Explanatory Shift

In the current study, we call the phenomena that is an explanation fundamentally reconstructed from a preceding explanation "an explanatory shift." We define the explanatory shift as a reconstruction of an original explanation that includes changes to both the structure of an explanation and the meaning of facts related to the explanation. Such changes neither partially expand a preceding explanation nor refine it. A preceding explanation is defined as "an initial explanation." We also call a reconstructed explanation "a shifted explanation." The explanatory shift is characterized by the perception of "a key fact" that must be fundamentally revised from the initial explanation. Namely, in the before and after stages of an explanatory shift, the meaning(s) of the key fact are fundamentally different.

As an example, consider the change of the caloric theory to the oxygen theory. Initially, in the caloric theory, burning was explained as the release of calories. After an inconsistency was observed in this explanation, i.e., the increase in weight after burning, a new explanation was required. The change of the explanation from the caloric theory, i.e., burning releases calories, to the oxygen theory, i.e., burning is associated with oxygen, was established by reinterpreting the key fact, i.e., the increase in weight by burning(S. F. Mason, 1953).

The Difficulty of an Explanatory Shift

It is difficult to shift the mind to a new explanation from an initial explanation by reinterpreting a key fact when it requires overcoming an accepted fact that in the past seemed to be common sense. For example, it has been repeatedly demonstrated that a confirmation bias leads to gathering positive instances that confirm an established hypotheses (e.g., Wason, 1960) and initial hypotheses are typically maintained against anomalous data(e.g., L. Mason, 2001). Therefore, even when an initial explanation is rejected and a new explanation is required, the initial explanation is protected by local modification and slight expansion with non-existent facts rather than the acceptance a new understanding by an essential change of the initial explanation.

In the oxygen theory, the connection of burning with oxygen explains a key fact; however, in the caloric theory, there

was only an assumption to support the release of phlogiston that had negative weight, which was part of the accepted theory even though the negative-weight phlogiston had not yet been observed or proved. Moreover, in the oxygen theory, as the explanation shifted from the caloric theory, the relationship of oxygen to burning could be accurately reinterpreted by overcoming an accepted common sense fact that had been accepted since the times of ancient Greece: "fire is an element."

Difficulties exist in such essential reconstructions of explanations. However, few studies have examined the process of the explanatory shift.

Transition of Attention toward an Explanatory Shift

In our previous research(Terai, Miwa, & Matsubayashi, 2012), we used eye-movement analysis to examine the transition of attention to a key fact that was contradictory to an initial explanation.

In the experiment, a short story is set in a town with only two barbershops (Figure 1). A character is looking for a barber and must pick one of the two shops. Barber A's staff has unkempt hair, while barber B's staff has hair that is beautifully cut. Initially, participants typically select barber B on the basis of the following naïve explanation provided as the initial explanation: "A barber with beautiful hair is very skilled." However, a new explanation is now required by the character for selecting barber A. The fact "barber A's hair is messy and barber B's hair is neat" contradicts the initial explanation. Therefore, in the story, the key fact that must be reinterpreted is "barber A's staff has unkempt hair and barber B's staff has neat hair." The reconstructed explanation from Gardner (1978) is "each does the other's hair because there are only two shops in town; therefore, barber A's staff, who did barber B's staff's hair, is more skilled." In the shifted explanation, the key fact becomes evidence for selecting barber A, but in the initial explanation, it is evidence for selecting barber B. The meaning of the key fact has completely shifted with the transition from the initial to the shifted explanation.

The experimental results are summarized as follows. First, the attention to the key fact, which is inconsistent with the initial explanation, declines. Second, the successful group increases their attention on the key fact just before the explanatory shift. Finally, we could facilitate the explanatory shift by both highlighting the key fact to lead the participants' attention to the key fact and instructing participants that the highlighted fact was crucial for finding the right explanation.

Relation between the Observation and the Explanatory Shift

The results of our previous research (Terai et al., 2012) show that the explanatory shift is facilitated by leading the participants' attention to a key fact by highlighting it and then instructing that the highlighted fact is crucial for finding the right explanation. However, it is unclear whether it is enough to only increase the chance of gathering information about the key fact or, in addition to this, there must be an intention to reconsider the meaning of the key fact in order to facilitate an explanatory shift.

Grant and Spivey (2003) discussed the relations between achieving insight and attention by inducing gaze in participants. In the experiments, the X-ray problem (Duncker, 1945), consisting of a tumor, healthy tissue wrapping around the tumor, and outer skin, was presented to the participants. They were required to solve how to destroy the tumor without harming the healthy tissue[1]. The results of the experiments revealed that problem-solving performance was increased by inducing the participants' attention (gaze) to the area in which the successful participants increased attention. Therefore, it is suggested that an explanatory shift is facilitated by having the opportunity to obtain the key fact from the bottom-up.

On the other hand, taking time to only see the key fact might be insufficient to shift an initial explanation. It is known that seeing is affected by knowledge held by the investigator, even in scientific activities where objectivity is required, i.e., the theory-ladenness of observation(Duhem, 1914; Hanson, 1958; Kuhn, 1962) . For example, in astronomy, Tycho and Simplicius saw a mobile sun, whereas Kepler and Galileo saw a static sun(cf., Hanson, 1958). This means that facilitation of an explanatory shift might require reflective thinking as a top-down process, which tries to reconsider a phenomenon from a different perspective.

Purpose

Our experimental purpose is to reveal the factors that facilitate an explanatory shift. We focused on the observation of a key fact, which is required for reinterpretation to achieve explanatory shift.

In our previous study, the attention on a key fact was inhibited, and then attention on the key fact was increased just before the explanatory shift as discovered through eye-movement analyses. However, the previous study did not sufficiently discuss differences of attention on the key fact between successful and unsuccessful groups. The degree of accuracy of eye-movement measurement is one of the reasons. Therefore, in experiment 1, we capture differences in the amount of attention on the key fact between successful and unsuccessful groups through more precise eye-movement measurement. Moreover, we reconfirm that moving the attention to the key fact is a robust process.

Then, in experiment 2, we discuss the factors that facilitate an explanatory shift by controlling both the bottom-up and the top-down processes: the opportunity to obtain the key fact and reflective thinking, which involves the reconsideration of a phenomenon again from a different perspective, respectively.

[1]The correct solution is the simultaneous convergence of low intensity X-rays on the focal tumor.

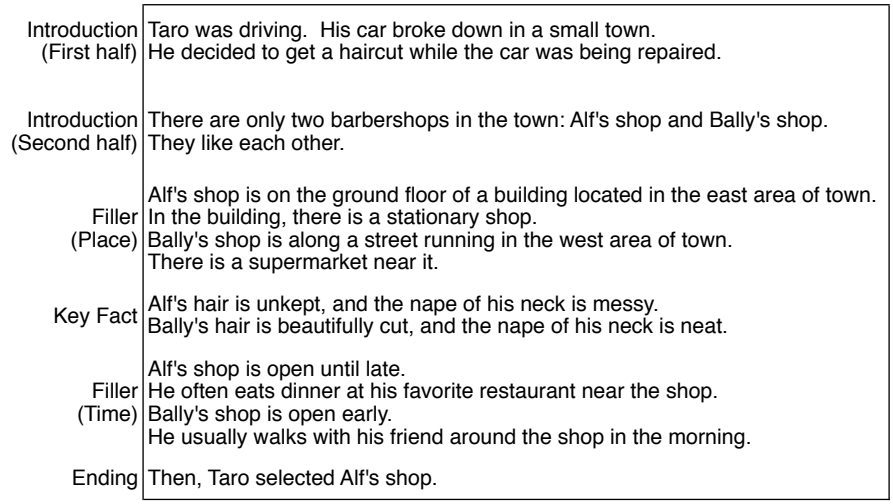

Figure 1: The barber task (modified from the original barber task in Gardner (1978))

Note. The story in the above box was presented to the participants in experiment 1. The story consists of an introduction, facts of regarding the place, barbers, and time, and an ending.

Experiment 1

Methods

Participants Forty-two undergraduates participated in this experiment.

Task Figure 1 shows the barber story task used in this experiment as introduced in our previous research(Terai et al., 2012).

Procedure Experiment 1 consists of two phases: the initial explanation phase and the reconstruction phase. In the initial explanation phase, the participants read the story (Figure 1) without the ending on a computer screen while thinking about which barbershop to select. Their task was to construct an explanation for their decision. They reported their constructed explanation by using a computer keyboard. The initial explanation phase was followed by the reconstruction phase in which the initial explanation was rejected, and they were required to reconstruct their explanation of the story. They reported their initial explanation and reconstructed explanation at their own pace. After reporting their explanations, they received the following message: "Since there is another reasonable explanation for this quiz acceptable to all, please reconsider another creative explanation." They were told that there was an evaluator in another room connected by the Internet, even though no such evaluator existed, and the same message was always returned. The reconstruction phase continued for 15 min, and then the data were analyzed until they reached the shifted explanation.

The experiment was conducted individually, and participant eye movements were recorded using a Tobii T60 eye tracker. In the experiment, we used a chin rest and required the participants to inhibit their head movement to increase the precision of gathering eye movement.

Results

Ten of 39 participants (three participants were excluded because of equipment trouble) constructed the initial explanation in the initial explanation phase and then constructed a shifted explanation in the reconstruction phase (the successful group). On the other hand, twelve participants could not construct the shifted explanation in the reconstruction phase, although they constructed the initial explanation in the initial explanation phase (the unsuccessful group).

In the following analysis, we focus on fixation ratios of each of the facts (introduction, place, key fact, time, and ending) in both the successful and the unsuccessful groups. Average fixation ratios of each fact were normalized by the number of characters in each paragraph corresponding to each fact.

Unsuccessful Group Figure 2 (a) shows the average fixation ratios in the first 5 min of the reconstruction phase in the unsuccessful group. To examine differences in the fixation ratios among each fact, a one-way analysis of variance (ANOVA) showed a significant main effect of the facts. The results of the multiple comparisons using Holm's method showed that the fixation ratio of the key fact was significantly lower than those of the place and time facts ($MSe = 0.00, p <$ .05).

Next, we examined whether there were any differences between the fixation ratios of each fact and the baseline calculated with assumption that each fact was seen in unbiased way. A t-test indicated that the fixation ratio of the key fact was lower than the baseline ($t(11) = -5.36, p < .01$). Moreover, a t-test indicated that the fixation ratio of the place fact was greater than the baseline ($t(11) = 2.24, p < .05$).

Successful Group An average time of constructing the shifted explanation in the successful group was 219.3 s ($SD =$ 179.0). Figure 2 (b) shows the average fixation ratios up to 30 s before constructing the shifted explanation in the successful group. A one-way ANOVA showed no significant main effect of the six facts ($F(5,40) = 1.36, ns$) whereas a t-test indicated that the fixation ratio of the key fact was lower than the baseline ($t(8) = -4.39, p < .01$).

Figure 2 (c) shows the average fixation ratios during 30 s until constructing the shifted explanation. A one-way ANOVA showed a significant main effect of the six facts ($F(5,45) = 7.48, p < .01$). The results of the multiple comparisons using Holm's method showed that the fixation ratio of the key fact was significantly higher than those of other facts ($MSe = 0.02, p < .05$). A t-test also indicated that the fixation ratio of the key fact was higher than the baseline ($t(9) = 4.70, p < .01$), whereas the fixation ratio of the first half of the introduction was lower than the baseline ($t(9) = -5.19, p < .01$).

The results of the experiments are summarized as follows: (1) The attention of the key fact, which is inconsistent with the initial explanation, declined and (2) the successful group increased their attention on the key fact just before the explanatory shift. These results are consistent with the experimental results in Terai et al. (2012).

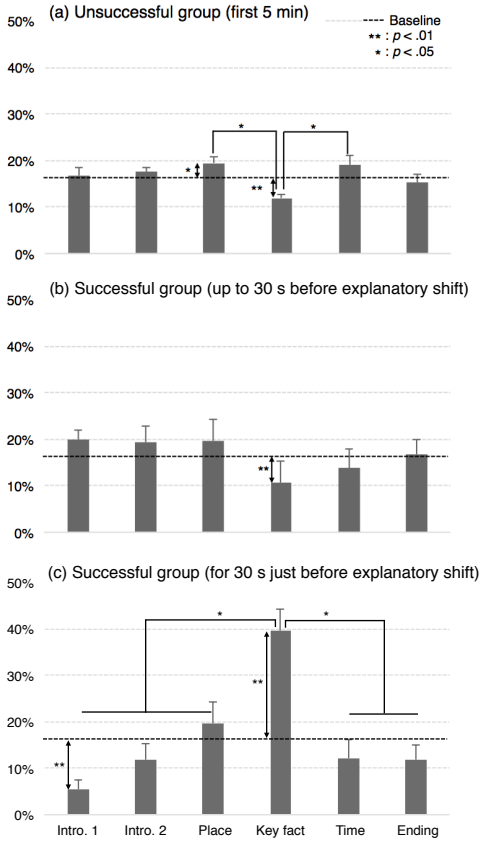

Figure 2: Average fixation ration of each fact.
Note. Each bar chart shows the average fixation ratios in the reconstruction phase. Error bars indicate standard errors.

Experiment 2

In experiment 2, we discuss factors to facilitate an explanatory shift by controlling both the bottom-up and the top-down processes: the opportunity to obtain the key fact and reflective thinking, which tries to consider a phenomenon from a different perspective.

Method

Participants Eighty-eight undergraduates participated in this experiment.

Task We used a barber task that was slightly modified from the one used in the previous experiment. In addition, in the reconstruction phase, we changed the procedure of the presentation of the story to control the rates of seeing each fact. In particular, each primal fact (place, key, and time facts) was repeatedly presented rather than having the whole story displayed at one time.

Conditions In addition to the control condition, we introduced three experimental conditions (bottom-up, top-down, and bidirectional). In the bottom-up condition, we controlled the observation time of each fact. In particular, the observation time of the key fact was twice (20 s) as long as that in the control condition, where the observation time of each fact in each period was 10 s.

In the top-down condition, we instructed the participants to reconsider a new explanation with reflective thinking. In particular, the participants were instructed to listen to instructions for reflective thinking through a set of headphones. Sentences in the instructions are as follows: (1) "Try to consider a new explanation without being bound to the initial explanation." (2) "Try to consider a radically new explanation." (3) "Try to consider a new explanation only on the basis of the presented facts." (4) "Try to consider a new explanation without adding any unobserved fact(s)."

The order of these instructions was randomized. During the vocal playback of each instruction, each fact was temporarily hidden. In the control and bottom-up conditions, these instructions were not given, while each fact was hidden at the same time in the bottom-up condition.

In the bidirectional condition, experimental manipulation was the combination of the bottom-up and top-down conditions. In particular, the participants observed the key fact for twice as long as the others and they were instructed to listen to the directions for reflective thinking through a set of headphones.

We conducted the experiment as a between-participants design (bottom-up: n = 20, top-down: n = 21, bidirectional: n = 23).

Procedure The procedure in the experiment followed that of the previous experiment. In the reconstruction phase, the observation time of each fact (place, key, and time) and the instructions for reflective thinking were controlled.

Results

Table 1 shows the results of success and failure of the explanatory shift. In the analyses, we excluded the participants who did not construct the initial explanation during the initial explanation phase. There was no significant difference among conditions where the successful participants who could shift their explanation in the bidirectional condition were greater than the ones who did in the other condi-

Table 1: Performance

Conditions	*n*	Shift	No shift
Control	17(24)	4	13
Top-down	17(20)	4	13
Bottom-up	15(21)	3	12
Bidirectional	20(23)	6	14

Note. Numbers in () refer to all the participants, including those who did not construct the naïve explanation.

tions.

Although there was no significant difference in the performance among the conditions,the experimental conditions might have influenced the process toward the explanation shift. Thus, we focused on the unsuccessful group (who could not form an explanatory shift). In the following analyses, we classified reconstructed explanations on the basis of their description to realize whether the participants tried to reinterpret the key fact. In particular, we defined the explanations that were based on the fact of the hair as "a pre-shifted explanation" in which participants were trying to reinterpret the key fact: e.g., "Because he had a full schedule and no time to fix himself up" and "Because Alf has hair and Bally is bald." On the other hand, we also defined explanations that avoided to reinterpreting the key fact were based on place and time facts and other facts not described in the story as "non-shifted explanations." In the following analyses, we compare each experimental condition with the control condition as the baseline.

Bottom-up vs. Control Figure 3 (a) shows the differences in the number of reconstructed explanations between the bottom-up condition and the baseline. In each explanation type, t-tests indicated no significant difference ($t(24) = -0.65, n.s.; t(24) = 0.96, n.s.; t(24) = -0.90, n.s.; t(24) = 1.24, n.s.$).

Top-down vs. Control Figure 3 (b) shows differences in the number of reconstructed explanations between the top-down condition and the baseline. In the non-shifted explanations based on the place and time facts, t-tests indicated no significant difference ($t(23) = 1.42, n.s.; t(23) = 1.43, n.s.; t(23) = 0.88, n.s.$). On the other hand, In the non-shifted explanations based on other facts, the number of reconstructed explanations in the top-down condition were lower than those in the baseline ($t(23) = -2.17, p < .05$).

Bidirectional vs. Control Figure 3 (c) shows differences in the number of reconstructed explanations between the bidirectional condition and the baseline. In non-shifted explanations based on the place and time facts, t-tests indicated no significant difference ($t(25) = 2.02, n.s.; t(25) = 0.28, n.s.$). On the other hand, In non-shifted explanations based on other facts, the number of reconstructed explanations in the bidirectional condition were lower than those in the baseline ($t(25) = -3.35, p < .005$). Moreover, in the pre-shifted explanations based on the key fact, the number of reconstructed explanations in the bidirectional condition were higher than those in the baseline ($t(25) = 3.20, p < .005$).

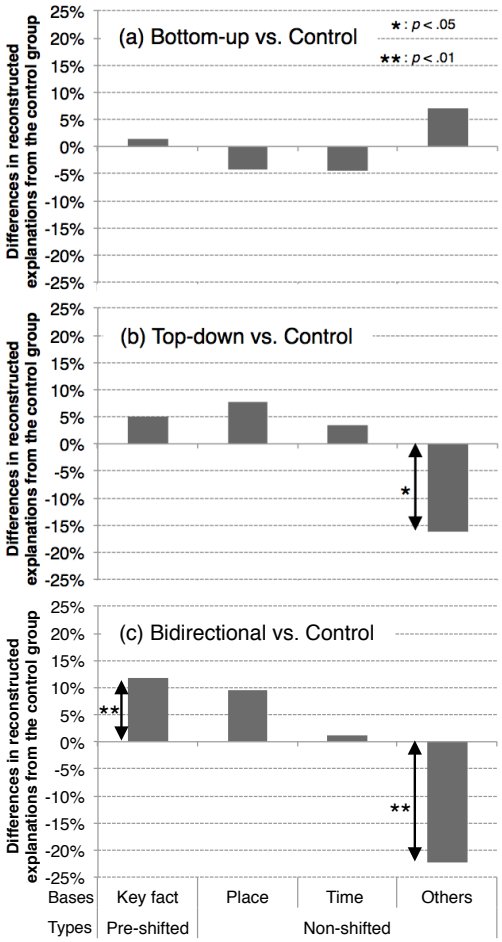

Figure 3: Types of reconstructed explanations

Discussion

Summary

The experimental results in experiment 1 are summarized as follows. First, when the initial explanation was rejected, a new explanation was required after attention on the key fact was inhibited. Second, the successful group increased their attention on the key fact just before the explanatory shift. These results are consistent with the results of Terai et al. (2012).

The experimental results in the experiment 2 are also summarized as follows. First, protection of the initial explanation with unobserved facts, i.e., constructing a non-shifted explanation, was not inhibited by only guiding the participants ' attention toward the key fact. Second, although the initial explanation was not completely shifted, a explanatory pre-shift was achieved by activating reflective thinking with attention on the key fact.

Explanatory Shift and Seeing

The experimental result that increasing the opportunity to obtain the key fact from bottom-up was insufficient to the explanatory shift is consistent with the theory-ladenness of observation. Namely, even if the chance to see the key fact in-

creases, the explanatory shift might not be facilitated because the perspective remain unchanged.

In problem-solving research, the Einstellung (set) effect is known to occur when the first idea that comes to mind, triggered by familiar features of a problem, prevents a better solution from being found(Bilalić, McLeod, & Gobet, 2008; Luchins & Luchins, 1950). Moreover, functional fixedness is well known as one of the cognitive biases that limits people to using a daily object only in the way it is traditionally used(Duncker, 1945; Scheerer, 1963).

Therefore, an underlying initial explanation leads a person to see a key fact with a bias. Then, the initial explanation will not be shifted even if the opportunity of seeing the key fact is increased.

Explanatory Shift and Reflective Thinking

The results of experiment 2 revealed that the focus of participants on the presented facts rather than non-existent facts facilitated by the reflective thinking (the top-down condition). Moreover, reflective thinking coupled with increasing the opportunity of gathering information about the key fact led the participants to construct a pre-shifted explanation (the bidirectional condition).

The dual process theory considers that high-order cognition consists of different types of systems, i.e., System 1 and System 2(Evans, 2003; Kahneman, 2011; Stanovich, 2004). System 1 is fast, parallel, automatic/unconscious, and intuitive, whereas System 2 is slow, serial, temporal, and requires conscious attention. Facilitation of reflective thinking might affect System 2. Stanovich's tripartite model of the mind based on the dual process theory suggests that System 1 corresponds to the autonomous mind and that System 2 is divided into two subsystems, the algorithmic mind and the reflective mind. The reflective mind inhibits an automatic response by the autonomous mind and activates the algorithmic mind to start calculating an alternative solution. The instruction that requires reflective thinking in experiment 2 might correspond to making an effort by the reflective mind to inhibit an automatic response to the key fact and to reinterpret the key fact in the algorithmic mind.

Explanatory Shift and Cues

In an insight problem-solving study, Grant and Spivey (2003) induced the participants' attention to the skin by subtly pulsing the skin area of a diagram in the X-ray problem. The thickness of its outer edge increased and decreased by one pixel three times per second. Such experimental manipulation might not only increase the opportunity of information gathering from the bottom-up but also provide a cue, which is essential for problem solving.

Similarly, in our previous research(Terai et al., 2012), we could facilitate the explanatory shift by both highlighting the key fact to lead the participants' attention toward it and instructing the participants that the highlighted fact was crucial for finding the right explanation. The bidirectional condition in experiment 2 of the present study lacked a cue that gave an information about where to direct reflective thinking. Such cues might be crucial to facilitate an explanatory shift.

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