Three barriers to effective thought experiments, as revealed by a system that externalizes students' thinking

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Abstract

This study aimed to develop a Thought Experiment Externalizer (TE-ext) and to apply it in order to observe barriers to problem solving. TE-ext enables students to visualize a problem situation. Users of TE-ext can implement changes in the situation and see the result as an animation. Experimental use of TE-ext identified three barriers to conducting an effective thought experiment (TE). First, participants tended not to change the situation from the original one; second, incorrect or inappropriate knowledge was applied to the situation; third, the participants did not apply the results of their TE to other situations. These factors prevented participants from rejecting their initial incorrect model and finding a new one through TEs.

Keywords: Thought experiment; scientific reasoning; science education system; problem solving

Introduction

Interest in thought experiments (TEs) has increased in recent decades (Matthews, 2014; Nersessian, 1992). A TE is an experiment conducted in one's mind. In this paper, we describe an effort to externalize TEs through a system that we call a Thought Experiment Externalizer (TE-ext). Initially, we review previous studies and identify research needs. Next, we introduce the TE-ext and our experiments using this system. Finally, we discuss the potential of TE-ext as an educational system.

Previous Studies

Previous studies can be divided into three categories based on their methods of collecting data.

Historical Research Some studies, particularly in the field of philosophy of science, have focused on specific historical cases (Brown, 1991, 2006; Nersessian, 2002). There are many renowned examples of TEs in history, such as those conducted by Galileo, Newton, and Einstein. Using these cases, the studies developed a definition of TEs and argued for their importance in the history of science.

Fieldwork Other studies have investigated the nature of TEs by collecting data in laboratories or classrooms (Lattery, 2001; Stephens & Clement, 2010). These studies have provided evidence that TEs are used not only by famous thinkers but by researchers, teachers, and students in their daily activities. Furthermore, they proposed cues to identify TE use and the types of situations wherein reasoners tended to conduct TEs.

Protocol Research Some researchers gave participants a physics problem and collected protocol data as the participants solved the problem (Clement, 2009; Kösem & Özdemir, 2014). They found differences between the TEs conducted by physics experts and novices. They also elucidated the TE process and its role in the scientific reasoning.

Summary of Knowledge of Thought Experiments Here, we briefly summarize the knowledge gained from these previous studies. There is no exact and agreed-upon definition of a TE, but Brown (2006) and Reiner (2006) proposed an operational definition. Their proposals were summarized by Kösem and Özdemir (2014) in terms of four steps, as illustrated below using the example of Galileo's TE that caused him to reject Aristotle's theory.

Step 1: Visualize a situation
(I am at the top of the tower with a heavy ball and a light ball)

Step 2: Carry out operation
(Connect each other ball and drop it from the tower)

Step 3: Apply background information
(Based on Aristotle's theory)

Step 4: See the result
(The theory leads to two contradictory results)

A TE involves visualizing a situation in one's mind and then imagining the result. It is a kind of mental simulation, which is a strategy in mechanical reasoning (Hegarty, 2004). The key step in the TE is the selection of the operation to be carried out in Step 2. Appropriate operations enable the reasoner to access implicit knowledge in Step 3, leading to a useful result in Step 4. Finally, a conclusion is drawn from the results of the TEs.

Justification for the Present Research

In this section, we describe what we consider to be the necessary research task from two perspectives.

Science Education Few studies have attempted to facilitate students' performance of TEs or to enable them to understand the benefits of TEs. Previous studies have been limited to examining the use of TEs by teachers and students in a daily classroom (Lattery, 2001; Stephens & Clement, 2010). Monaghan and Clement (1999) successfully facilitated mental simulation by means of a computer simulation. However, their face-to-face method would not be suitable for use with a large class.

Our TE-ext, which will be described below, has advantages for science education. Students can easily carry out operations because the available operations are visible. Additionally, the externalization of the TE reduces the cognitive load, making additional cognitive resources available for reasoning.

Psychological Research Almost all previous studies involved no experimental operations, as they focused on reasoning in a naturalistic situation. Protocol analysis has been a prominent method in these studies, since TEs are conducted in the reasoners' mind. These studies have contributed to our knowledge of the process and nature of TEs. Based on this accumulated knowledge, we can learn more about TEs through experimental operations.

Our TE-ext is a useful tool for psychological experimentation because it provides us with quantitative data, such as sequences of operations. In this study, we use TE-ext and some experimental operations to investigate barriers preventing students from conducting an effective TE.

TE-ext

Material

We used the yoyo problem from Anzai and Yokoyama (1984). The problem was to predict the movement of the yoyo in Figure 1. In our study, students had to decide in which direction the yoyo would move (left, right, or staying in place) and in which direction it would rotate (clockwise, counterclockwise, or remaining still). The correct answer was that the yoyo would rotate clockwise and roll to the right. The direction of rotational momentum caused by the tension force in the string and the center of rotation at the yoyo's point of contact with the floor determine the movement.

The yoyo problem had three advantages. First, Anzai and Yokoyama (1984) defined students' internal models. In the students' naïve model, they believed that the yoyo's axis was the center of the rotation. Based on this model, they answered that the yoyo would rotate counterclockwise and roll to the left. The second advantage was that a cue capable of causing the students to shift to a correct model had already been demonstrated. When asked to think about a square object instead of a round yoyo, the students predicted that it would be dragged to the right and realized where the center of the rotation was (Anzai & Yokoyama, 1984). This insight led them to the correct answer. Therefore, to solve the problem through TEs, it was important to carry out the mental operation of changing the yoyo's shape into a square and pulling the string. Finally, the effects of the predicted barriers at each step could be associated with particular responses to the yoyo problem (see the discussion on barriers below).

The centers of two circular frames are interconnected by an axle, and a string is wound round it as illustrated in the figure below. What will happen if you pull the string as shown in the figure?

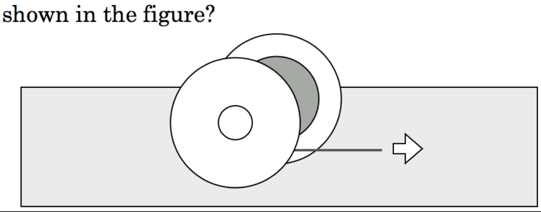


Figure 1: The yoyo problem.

System's Function

TE-ext externalizes Steps 1, 2, and 4 of the TE. Figure 2 shows sample screenshots of important parts of TE-ext. The properties of the yoyo shown in Figure 2(a) represented the problem situation, which was the initial state of TE-ext. The students could observe the yoyo from the side. Since TE-ext visualizes a problem situation on a PC monitor, users do not have to carry out the visualization in their mind in Step 1.

The students could carry out some operations on the yoyo in the TE-ext system, thereby externalizing Step 2 of the TE process. They could change the size and shape of the yoyo, the location of the end of the string, the width of the string, and the amount of string wound around the yoyo. The size and location of the end of the string could be changed by dragging the red and black rectangles, respectively. Other properties could be selected on the option panel (Figure 2(b)).

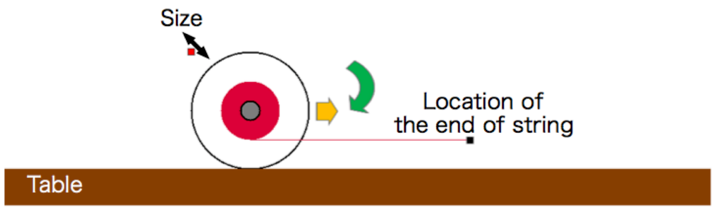
The students could then see the result (Step 4) in TE-ext by selecting a direction and clicking the "move" button. The direction of movement and rotation were selected using the animation buttons (movement: up, down, right, left; rotation: clockwise, counterclockwise). The yoyo in TE-ext moved in accordance with the selected buttons, even if such movement violated physical laws. The role of TE-ext was not to provide new knowledge but to externalize TEs; the animations were consistent with the fact that, in a TE, any prediction is possible. We then investigated barriers preventing students from conducting an effective TE using TE-ext.

Three Barriers

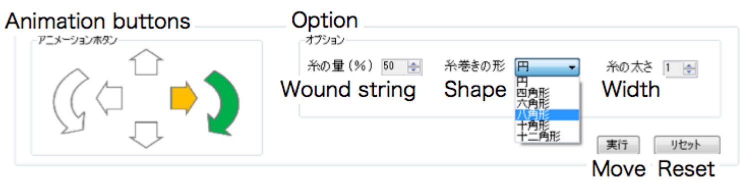
We defined an effective TE as one that causes students to shift their mental model. In scientific reasoning and problem solving, it is important to reject an incorrect model or concept and to find a new correct one (Vosniadou & Brewer, 1992). We predicted three barriers to an effective TE, or to achieving a shift in one's mental model through TEs, in alignment with the thinking steps described by Kösem and Özdemir (2014).

The first barrier would exist at Step 2, during which the students carry out operations. To conduct an effective TE, they have to change a situation into one invoking implicit knowledge that they could not apply to the initial situation. In the case of the yoyo problem, an operation to give the yoyo wheels a square shape is crucial. However, people are apt to avoid testing a situation that would violate their model (Wason, 1960). It would be difficult for most people to carry out an operation that makes the situation different from the initial one. Thus, students could be expected to conduct TEs in the original situation with round yoyos.

The second barrier would exist at Step 3. Even if students create a good experimental situation, they cannot always apply appropriate background information or knowledge. In this case, they may not be able to imagine the square-shaped yoyo being dragged to the right. It is easy for students to rely instead on the knowledge already in their mind. Therefore,



(a) The yoyo in TE-ext



(b) Option panel and animation buttons

Figure 2: Sample screenshots of TE-ext. Figure (a) shows the yoyo on the table; figure (b) shows the option panel and the animation buttons. The right and clockwise animation buttons are selected in the figure. Each shot captures important parts in TE-ext. The other part of the screen is used to display the yoyo's movement.

they may apply their incorrect model to the situation, leading to an inappropriate result.

The third barrier would exist at Step 4. The students have to derive a conclusion from the results of their TE. However, the results violating their current model are not easily applied to the solution of the original problem. In the yoyo problem, this would mean that the students, although they understand that a square-shaped yoyo is dragged to the right, would not be able to apply this result to the original round yoyo. Some previous studies have revealed that even when participants or scientists confronted contradictory data, they did not change their initial model (Chinn & Brewer, 1993; Dunbar, 1995). Instead, to retain their model, they reinterpreted the data or added peripheral explanations. The results of these studies suggest that the students cannot easily change their initial model, even if they see the appropriate results of a TE.

Using TE-ext, we investigated whether these barriers exist and whether we could eliminate them.

Methods

Participants

Nineteen undergraduate students participated in the experiment. Their major fields included literature, education, law, and economics. All students had basic knowledge of elementary physics from junior high school. Eleven of them had studied physics in high school; none had taken a physics course at the university level.

Procedures and Predictions

The experiments were composed of four phases. Procedures, aims, and predictions in each phase are summarized in Table 1. The students answered the same question in each phase. They observed a picture of the yoyo, read the problem as presented in Figure 1, and then selected the direction of movement and rotation. Additionally, they were asked to write down the reason for their decision.

Phase 0 included only the test. The aim here was to confirm that the students would answer "left and counterclockwise," which meant that they had the incorrect initial model. After Phase 0, the experimenter instructed the students on how to use TE-ext.

Following the introduction of TE-ext, Phase 1 was used to confirm the presence of the first barrier. During this phase, the students were asked to work on the yoyo problem for 10 minutes using TE-ext freely (i.e., thinking time) and then to answer the test question again. If the first barrier existed, it would prevent the students from carrying out suitable operations to change the situation from the original one. Therefore, they would conduct more animations with the round yoyo during their thinking time and therefore end up with the same result as in Phase 0.

We aimed to break the first barrier in Phase 2 by providing instruction along with thinking time and the test. First, the experimenter instructed the students, as a means of solving the yoyo problem, to change the properties in TE-ext to make the situation different from the original one. Additionally, she showed some examples of possible situations, including the square-shaped yoyo. After this instruction, the students worked on the yoyo problem for 10 minutes and then took the test again. If the instruction had overcome the first barrier, the students would conduct animations with yoyos of various shapes including a square one, during their thinking time. However, even if the first barrier was gone, the students would still be likely to select the answers of left and counterclockwise on the test due to the second and/or third barriers.

Phase 3 had two purposes. First, we investigated whether the second or third barrier prevented the students from reconsidering their thinking; second, we tried to break the third

Table 1: Procedures, aims, and predictions.

Procedure		Aim	Prediction
Phase	Step involved		
Phase 0	Test	Identify the students' initial model	Students will select "left and counterclockwise" based on their incorrect model.
Phase 1	Thinking time	Confirm the existence of the first barrier	If the first barrier exists: → Students will conduct more animations with the round yoyo and select "left and counterclockwise."
	Test		
Phase 2	Instruction	Break the first barrier	If the first barrier is broken: → Students will conduct animations with various yoyo shapes.
	Thinking time		
	Test		
Phase 3	Additional test	Confirm the existence of the second and third barriers	If the second barrier exists: → The expected combinations, "right and still," will not be selected on the additional test. If the third barrier exists: → Students will not arrive at reach the correct model even if they do not have the second barrier.
	Instruction		
	Thinking time	Break the third barrier	If the third barrier is broken: → Students will select "right and clockwise" on the test.
	Test		

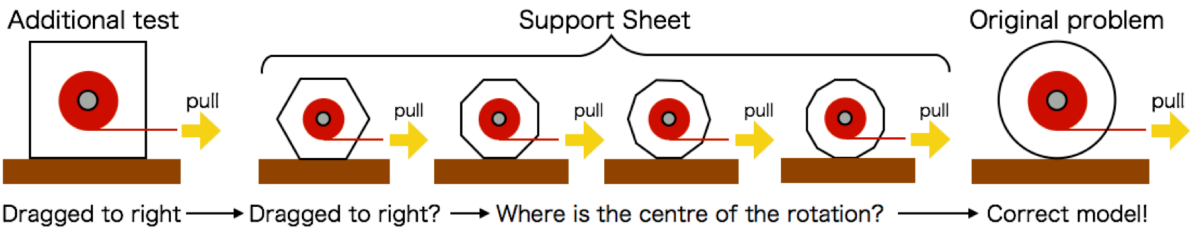


Figure 3: An image showing the mental process of solving the yoyo problem by using the additional test and the support sheet.

barrier. (Breaking the second barrier was outside the scope of our study, as the second barrier exists at Step 3, which TE-ext did not externalize.) Phase 3 included an additional test, instruction, thinking time, and the original test.

In the additional test, the students were asked to indicate the movement of the square-shaped yoyo (shown at the far left in Figure 3) just as they had done for the round yoyo on previous tests. We conducted this additional test to investigate the existence of the second barrier (i.e., the first purpose). If the second barrier prevented the students from using their knowledge appropriately, they would not select the expected choices (movement to the right, remaining still with regard to rotation).

To address the second purpose of Phase 3 (trying to break the third barrier), we targeted those students who selected incorrect combinations on the original test in Phase 2 and "right and still" on the additional test. They must have been prevented from shifting their model during Phase 2 by the third barrier. The additional test served as a cue for them, as suggested by Anzai and Yokoyama (1984).

We gave these students an additional "support sheet" including choices of movement for hexagonal, octagonal, 10-sided, and 12-sided yoyos. This bridged the gap between the square-shaped yoyo and the original round yoyo, as shown in Figure 3. We instructed the students to make predictions about the yoyos on the support sheet and then to solve the original yoyo problem based on their predictions for 4- to 12-sided yoyos. With this assistance, the students were given another 10 minutes of thinking time to use the TE-ext, the additional test, and the support sheet. Finally, they took the original test one more time. If we had successfully broken the third barrier by this point, they would imagine a correct model and select "right and clockwise."

Results

Model Shift

In Figure 4, we show the students' selections in each phase of the test. The correct answer is "right and clockwise." No student selected the correct combination, except for one student in Phase 0 who then changed his answer in Phase 1. In all phases, the selection was not equally distributed (Fisher's exact test $ps < .05$). The number of students who selected "left and counterclockwise" was significantly larger than the expected value in all phases ($ps < .002$). These results show that the shift to a correct model did not occur.

First Barrier

Figure 5 shows a ratio that indicates how frequently each shape was selected when the "move" button was clicked.

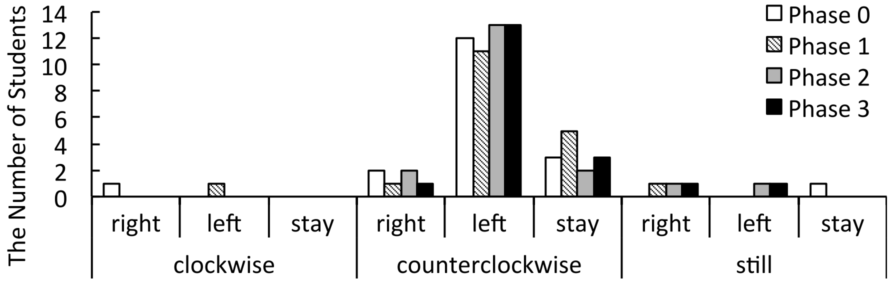


Figure 4: The student's selections on the test in each phase.

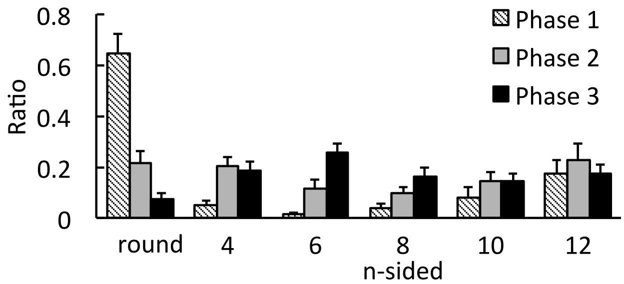


Figure 5: The ratio of the number of animations with each shape to all animations (bar represents standard error).

We conducted a 3 (phase) $\times$ 6 (shape) ANOVA. There was a significant interaction between the phase and shape factors ($F(10,180) = 13.84, p < .001$). Here we focused on the effect of the shape factor according to our purpose. In Phase 1, a simple main effect of the shape factor was significant ($F(5,90) = 26.412, p < .001$). The round yoyo was selected more frequently than other shapes were (ps $< .05$). In Phase 2, there was no significant effect of the shape factor ($F(5,90) = 1.376, p = .241$). In Phase 3, the simple main effect was significant again ($F(5,90) = 2.826, p = .020$). The only difference was that the hexagonal yoyo was selected more frequently than the round yoyo was ($p = .050$). A main effect of the shape factor was significant ($F(5,90) = 7.567, p < .001$). The preference for the round yoyo in Phase 1 means that the first barrier prevented the student from changing the situation from the original one. The instruction in Phase 2 broke this barrier, so that the preference disappeared. However, the various situations, including the square-shaped yoyo, did not lead the students to the correct model (Figure 4). This failure must be due to the second and/or third barriers.

Second Barrier

Figure 6 shows the selections made on the additional test and the support sheet. In the additional test, the selections were not equally distributed (Fisher's exact test $p = .024$). The number of students who selected the expected answer, "right and still," was significantly larger than the expected value ($p = .002$). This means that about half of the students who selected "right and still" did not have the second barrier. However, other students selected unexpected combinations. Although we cannot know why they did so, their incorrect model must have affected their selection. This result shows that half of the students could not arrive at the correct model because of the second barrier.

Third Barrier Half of the students did not have the second barrier. However, in the test in Phase 2, they were still unable to select the correct combination (Figure 4). This implies the existence of the third barrier.

In Phase 3, we attempted to break the third barrier using some supportive information. Despite these efforts, no student was able to select the correct combination on the original test (Figure 4). The reasons given for their decisions reveal that they added inappropriate or incorrect explanations to justify retaining their initial model. For example, a student who selected the expected combination on the additional test but stuck with "left and counterclockwise" on the original test wrote, "a round shape is easier to roll [to the left than other shapes] because of the small friction force." These results mean that our supportive assistance could not break the third barrier.

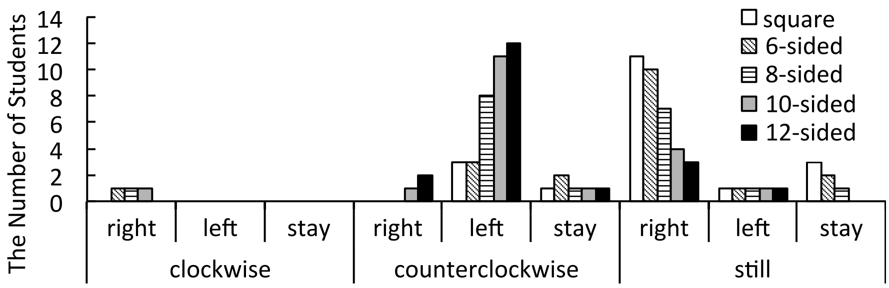


Figure 6: The number of students selecting each combination on the additional test and the support sheet.

General Discussion

In this study, we developed TE-ext, a system that permits observation of individuals' thought experiments, and used it to investigate the three barriers to an effective TE. We found that none of the students could make the shift to a correct model. All students experienced the first barrier, and half of them exhibited the second barrier. Even when students did not have the second barrier, the third barrier prevented them from shifting to a correct model. Although we successfully broke the first barrier by means of our instruction, the support sheet designed to break the third barrier did not have sufficient effects.

Almost all students continued to hold to their initial, incorrect model. They added inappropriate or incorrect peripheral explanations, as is typical of people dealing with information contrary to their beliefs (Chinn & Brewer, 1993; Dunbar, 1995). We need to break the third barrier to use TE-ext as an educational system.

One possible reason why our supports had no effect on the third barrier is that the students had incorrect models that differed from what we anticipated. Our students had different academic majors from the science and engineering students who participated in Anzai and Yokoyama (1984)'s study. The reasoning given for their selections on the test showed their belief that when the string was pulled, a force unwinding the wound string was present and the yoyo rolled in reaction to this force. Our supportive information in Phase 3 did not focus on this point, so it had little effect on this belief.

Regarding the potential educational use of TE-ext, we expected that the students would realize the benefits of TE by solving the yoyo problem successfully using TE-ext. Unfortunately, no one was able to shift to a correct model in our experiment. The following improvements, suggested by the results of our experiment, could make TE-ext a more powerful educational tool.

Improvement of TE-ext to help students visualize situations in daily life would be effective to break the second barrier. In such situations, they can draw on their own experience to see the result. Kösem and Özdemir (2014) showed that novices tended to use their own experiences as resources when conducting TEs.

Adaptive supports causing each student to conduct TEs suitable for his or her own incorrect model would help break the third barrier. In this study, our supports were not effective in modifying the students' initial model. If TE-ext could be improved by incorporating each student's cognitive model, it could adaptively provide TE situations suitable to instruct that student.

Additionally, TE-ext could work more effectively in a group setting. Students could share their TEs with each other by using TE-ext. TE-ext would serve as a hub connecting the students and their thought processes (Nersessian, 2009).

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