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Factors Triggering Thought Experiments in Small Group Physics Problem-solving Activities

Hartono BANCONG
Department of Physics Education, Universitas Muhammadiyah Makassar, Makassar 90221, Indonesia

Jinwoong SONG*
Center for Educational Research, Seoul National University, Seoul 08826, Korea

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This study sought to identify the factors that trigger the emergence of thought experiments when students interact with each other in their groups to solve problem. This study had 12 participants, six master's students and six undergraduate students in three different universities in Indonesia. The participants were divided into three groups so that each group consisted of four students. Small-group physics problem-solving activities were used for observing the factors that encourage students to construct thought experiments. The results showed five factors that encourage students to visualize imaginary worlds as an initial step in constructing thought experiments: conflicting ideas, similar ideas, support from experienced people, students' bodily knowledge, and students' imaginary visual knowledge. This indicates that thought experiments can occur not only because of students' personal knowledge (imaginary visual knowledge and bodily knowledge) but also because of interactions among students in a group to solve a problem (conflicting ideas, similar ideas, and support from experienced people). Therefore, we think that placing students into a group is an effective way not only to encourage students to perform thought experiments by utilizing each other's resources and skills but also to increase social interaction and support diversity.

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I. Introduction

Scientific inquiry has been considered as one of the main goals in science education since the 1960s [25]. Scientific inquiry was originally used as an effort to involve students in thinking processes and activities similar to those practiced by scientists [3,16,21,25]. Through scientific inquiry, students will be encouraged to develop the thought processes involved in creating facts, generating new explanations, and justifying explanations [19,21,25].

Throughout the history of physics, there are two types of experimentation that are used by physicists to justify explanations or facts: real experiments and thought experiments (TEs) [4,19,22,27,31]. Real experiments have been widely accepted by physics educators as a learning tool and well integrated into the curriculum. On the other hand, TEs still receive less attention even though they are inherently embedded in the culture of physics [1,12,27]. The role of TEs cannot be replaced by real experiments because TEs allow situations that are usually impossible to be reproduced by real experiments regardless of the sophistication of the equipment [9,12]. TEs also idealize the conditions of real experiments with complex technical details, experimental errors, and inhibiting factors (heat, friction, etc.) [9,12]. In addition, TEs are indispensable in teaching modern physics: the relativity theories and quantum mechanics, where real experiments are practically impossible to be implemented in regular classroom activities and multimedia tools very often fail [12].

*E-mail: jwsong@snu.ac.kr

Some related literature has emphasized that visualization is the main feature of TEs [5,13,15,27]. Gooding [15] argued that TEs in physics do work because of the visualization process that directs thought experimenters to embodied inferences. Both Reiner [27] and Brown [5] also proposed several similar structures of TEs where visualization is the first step in the TE process. Reiner and Gilbert [29] had investigated a series of TEs performed by teachers and students when they were working on problems and identified two epistemological resources for TEs visualization: visual imagery and bodily knowledge. They claimed that these two factors — visual imagery and bodily knowledge — inspired teachers and students to visualize imaginary worlds as the first step in generating TEs. Visual imagery refers to individual abilities in imagistic simulation, while bodily knowledge refers to physical experiences, such as riding bikes or playing basketball [29].

TEs are important in teaching and learning of physics. Some studies have shown that the use of TEs in teaching physics has potential to familiarize students with the culture of physics [1,12,27], help deepen students' understanding of physics concepts [2,12,17], inspire students to provide a rich source for their ideas [20], and develop students' intuition [14,28,35]. TEs can also expose students' hidden reasoning [7,18], promote imagistic simulation [32], and help students' imagination to develop [12]. After implementing Heisenberg's historical TE of the microscope as a tool in teaching the uncertainty principle to high school students, Velentzas and Halkia claimed that historical TEs have great potential as tools to teach physics topics that demand sophisticated conceptual understanding [33].

However, there is still little understanding of how students are involved in the process of constructing TEs in group learning. Previous studies have focused more on the TEs' processes at the individual level rather than in groups [1,7,14,18,32]. Although Reiner [27] argued that TEs are more easily constructed in a collaborative manner, how TEs are constructed collaboratively are not clearly explained either by Reiner [27] or subsequent studies. In particular, there is a lack of understanding of the factors that encourage students to do TEs in collaborative learning. Reiner and Gilbert [29] have released two factors that encourage both teachers and students to do TEs, however, both of these factors are of individuals.

The purpose of this study, therefore, was to identify the factors that encourage students to construct TEs while solving physics problems in small groups. In our previous study, we explored the processes of students construct TEs in small group physics problem-solving activities. The results showed that TEs could be designed and constructed in a collaborative manner even though they are mostly individual in nature. Therefore, this study is a follow-up to the previous one. In this study, we organized students involved in group learning to construct TEs during physics problem-solving. In small-group learning, students have opportunity of communicating with other students by asking, supporting, clarifying, and validating ideas in order to construct TEs. Therefore, TEs, in a group learning setting, provide many benefits for students because students can access various types of experiences, resources, and understanding. In addition, because TEs are basically mental model activities that are carried out mostly in the minds of individuals [26,29], some students have difficulty in constructing TEs independently [1,5,18]. In group learning, students who have difficulties or less capacity will be helped by others because they can use each other' s resources and skills (e.g. experience, knowledge, and logic).

II. Literature Review

1. The meaning of thought experiments

A large number of studies have been carried out in a variety of areas such as philosophy, history, and education that have contributed to the TE literature by examining their significance, function, and role in learning and teaching. Nevertheless, a consensus has still not been reached on the exact definition of a TE. As Brown [5] said, "we know thought experiments when we see them. But there is no point in trying to define thought experiment any more than there is in trying to define loyalty, religion, or a meaningful life" (p. 63). Only a few characteristics of TEs are known, such as they are performed in a personal mind, involve mental manipulations, and are not the mere consequence of a theory-based calculation [4,5].

The term TE, a direct translation of the German term Gedankenexperimente, first appeared in English translations of Ernst Mach's [22] paper that viewed TEs as ways of scientific thinking. Even though some researchers have argued that the term had already been used by Danish physicist Hans Christian Ørsted in 1811 [17,34], Mach was considered as the first to introduce this construct into active use, particularly in education [12,23]. In his paper "On Thought Experiments", Mach [22] stated that

I have seen this method [TE] in operation both in the case of my own high school teacher, H. Phillipp, and also when visiting the school of F. Pisko, another admirable pedagogue. Not only the pupil but also the teacher gains immeasurably by this method: it is the best way to get to know one's pupils. (p. 142)

Besides being effectively used as a method for guessing which problems can be solved and which cannot, TEs are important for professional inquirers and also for mental development [22].

To Nersessian [26], TEs are a form of reasoning:

While I agree with Norton that thought experiments can often be reconstructed as arguments, the [mental] modeling function [of the thought experiment] cannot be supplanted by an argument ⋯ On my view, thought experimenting is a complex form of reasoning that integrates various forms of information—propositions, models, and equations—into dynamic mental models. (p. 297)

Reiner and Gilbert also defined TEs as reasoning processes that represent the model of an event and start out in the mind of an individual [29]. Both Nersessian [26] and Reiner and Gilbert [29] agreed that the use of imagery in a TE enables the thought experimenter to accesses tacit knowledge (non-explicit knowledge) that acts as the basis for generating new states of knowing.

Some literature also typically describes TEs in terms of their function. For example, Sorensen viewed TEs as limiting cases of real experiments that can achieve the aim of real experiments without actually executing them [31]. Galili proposed that TEs are logical devices in our mind for developing, clarifying, and critiquing of theoretical conceptions [12]. Similarly, Stephens and Clement argued that TEs are activities that can be used to evaluate scientific concepts, models, and theories and even to predict aspects of a concrete system [32]. Therefore, based on these explanations, it can be drawn a common thread that TE is an experimental activity carried out in the mind of individuals with personal imagery that is usually used by scientists in formulating new theories, supporting or refuting existing theories.

2. The steps of conducting thought experiments

Some philosophers and historians view TEs as a continuum of REs that can achieve the goal of REs by simulating them in the mind of individuals and observing them with the mind's eyes [4,12,19,22,31]. Like REs, TEs are not random and undisciplined activities, but they operate on structured imagination. According to Reiner [27], the structure of TEs is divided into five stages. First, thought experimenters construct an imaginary world and describe the features of the world they imagined, such as objects, rules, and conditions. Second, thought experimenters set the hypotheses or general assumptions to be used, such as using a scientific theory. Third, thought experimenters design and conduct an experiment in their minds. Fourth, thought experimenters describe the results of the carrying out the experiment, and, fifth, thought experimenters draw conclusions.

Brown [5] also argued that TEs are carried out in a laboratory of the mind and have at least three steps: Thought experimenters (a) visualize the situation, (b) carry out an experiment, and (c) describe the results. Both Reiner [27] and Brown [5] proposed similar structures of TEs: visualize imaginary worlds, perform experiments, and describe the results. For example, the TE of Einstein's chasing a light beam [10] said:

If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however,

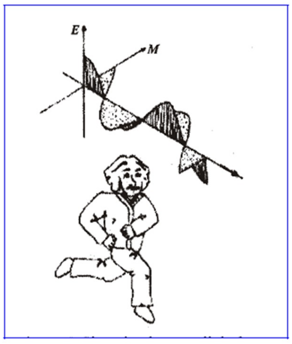

Fig. 1. (Color online) Einstein chases a light beam [15].

neither on the basis of experience nor according to Maxwell's equations (p. 53).

There are three components visible in this TE [5]. First, Einstein visualized an imaginary world by imagining himself chasing a beam of light that travels with speed c. Second, while chasing a beam of light, Einstein then observed the state of the light beam with his mind's eye, whether stationary or moving with speed c. Third, Einstein then described the results of his observations, which saw a beam of light like an electromagnetic field that looked static despite spatially oscillating. The result of this TE shows that the speed of light is not always the same as c. Einstein assumed that the speed of light would be 0 when he was able to catch the beam of light. Similarly, water skiers or runners on the beach will see stationary water waves when moving together, as Brown [5] said:

When he was only 16, Einstein wondered what it would be like to run so fast as to be able to catch up to the front of a beam of light. Perhaps it would be like running toward the shore from the end of a pier stretched out into the ocean with a wave coming in alongside [Figure 1]. There would be a hump in the water that remains stationary with respect to the runner (p. 67).

TEs consists of two aspects: thought and experiments [12,29]. The thought aspect involves visualizing an imaginary world that is related to theories and experiences of thought experimenter, while the experiment aspect refers to experiment activities in the real world, such as manipulating variables and objects. Therefore, based on the above explanations, TE is defined as a structured process of visualizing imaginary worlds where experiments will be designed and run in the head of individuals, and then the results of conducting experiments are explained. Three activities are used to detect the TE carried out by students while solving physics problems: visualizing imaginary worlds, performing experiments, and describing the results.

3. Thought experiments and problem solving

Some related literature has argued that TEs are cognitive tools for both students and experts when they are working on problems [7,18,22,27,29]. Mach emphasized the values of TEs as logical devices for guessing which problems can be solved and which cannot [22]. Reiner and Gilbert [29] investigated a series of TEs performed by teachers and students when they were working on problems. They claimed that both teachers and students solved problems using TEs as a logical tool. Clement [7] and Kösem and Özdemir [18] also investigated the role of TEs through physics problem-solving activities. They claimed that participants used TEs as a logical device to predict the solution of the problems, to confirm and discredit theories, and to give more explanation about their hypothesis.

Therefore, in this study, physics problem-solving activities were used to set the necessary conditions for observing the students' TEs. During the problem-solving sessions, we carefully observed the factors that encourage students to construct TEs.

III. Methods

1. Context and Ethics

To identify the factors that encourage students to construct TEs during physics problem-solving activities, we adopted and modified the physics problems from Epstein's book entitled Thinking Physics Is Gedanken Physics [11]. The book contains a series of physics problems that can trigger and activate the imaginary world of students to enable them to perform TEs while solving problems. The potential problems were discussed and then piloted with some students to check whether or not they encourage students to do TEs. After being piloted and discussed again, we decided 5 physics problems that are effective in stimulating and triggering students to do TEs.

As this study involved human participants, the Institutional Review Board (IRB) of Seoul National University monitored all procedures, including recruitment of participants, consent forms for the participant, data collection, and data analysis. This study received IRB approval (No. 1811/003-015). Following guidelines for conducting an ethical study, we used codes for all participants.

2. Participants

In this study, there were 12 participants: six master's students and six undergraduate students. They were pre- and in-service physics teachers at three different universities: Unismuh, UNM, and Unhas. All of these universities are located in Makassar, South Sulawesi province, Indonesia. The criteria for selecting participants for master's students were (1) receiving their undergraduate education from a teacher-training university and (2) being a graduate student majoring in physics or physics education. On the other hand, the criteria for selecting participants for undergraduate students were (1) being a pre-service physics teacher at a teacher-training university and (2) having not yet passed or taken the exam qualification as the main requirement for graduation. In order to capture the variation of the TEs processes in-depth and details, the participants were divided into three small groups according to the level of education. Each group consisted of four participants. Detailed information about the participants was presented in Table 1.

The aim of gathering data from Group 1 was to observe the process of TEs for a kind of expert. In this study, we chose a physics problem related to the fundamental physics laws on classical mechanics designed for first-year university students with the assumption that the expertise of master's students on this topic is higher than that of undergraduate students. The physics qualification exam for graduation was also set as a criterion for the undergraduate group because it provides further evidence of the competence of master's students on the basic concepts of physics.

On the other hand, Group 3 consists of undergraduate students. In this context, however, it does not mean that these students have a poor understanding of physics. Rather, this group consists of undergraduate students who have not yet taken or passed the physics qualifications exam for graduation. Group 2 is a combination of master's students and undergraduate students. It was set to observe the interaction that might occur between the master's student and undergraduate student in constructing TEs.

3. Data Collection

For the data collection, group observation and field notes were the primary methods for collecting the data. First, we presented the physics problems and provided a blank piece of paper to each group member to be used to write or draw on when explaining their thoughts to the other members for efficient communication. During problem-solving activities, we carefully observed the processes of TEs that occur while solving a physics problem. In each TE, there was a particular focus on identifying the factors that influenced students in constructing the TE. For each group, observation and recording were carried out five times, once for each of the physics problems the students worked on. In addition, in order to understand students' thinking, we asked questions about what the students were thinking and why they were thinking it at particular times during the problem-solving activities. For triangulation, we also collected data from the students' notes.

4. Data Analysis

As mentioned earlier, both Reiner [27] and Brown [5] proposed similar structures of TEs: visualize imaginary worlds, perform experiments, and describe the results. Therefore, these three activities were used

Table 1. Overview of participants in each group.

Group	Code	Gender	Age	School type		Grade
				Undergraduate	Graduate	
1	A1	Female	28	Unismuh	Unhas	Master's student
	A2	Female	24	Unismuh	Unhas	Master's student
	A3	Female	24	Unismuh	UNM	Master's student
	A4	Female	23	Unismuh	UNM	Master's student
2	B1	Male	24	Unismuh	UNM	Master's student
	B2	Male	23	Unismuh	UNM	Master's student
	B3	Female	21	Unismuh	-	Undergraduate student
	B4	Female	20	Unismuh	-	Undergraduate student
3	C1	Female	21	Unismuh	-	Undergraduate student
	C2	Female	21	Unismuh	-	Undergraduate student
	C3	Female	21	Unismuh	-	Undergraduate student
	C4	Male	21	Unismuh	-	Undergraduate student

as an indicator of the TE. In order to identify the visualization of TEs, the transcripts of the audio and video recordings, images from videotapes, and field notes were analyzed simultaneously. We used the framework for "imagery-related observation indicators" provided by Clement *et al.* [8] and Clement [7] to identify the indicators of visualization: (1) imaginary report: the subject says "imagining," "feeling," "suppose that," or other sensations; (2) hand motion: the subjects describe the object, force, or dynamic event while moving their hand; and (3) analogy: the subject uses a personal analogy by referring to an analogous situation involving body movements. The following is an example of how TE processes performed by a participant were detected during the participants solving a physics problem collaboratively.

R OK. Let's start from the first question . . . Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure [Figure 2]. What do you think?

[. . .]

A1 So, I think that there is no external force and no friction.

A4 Aaa, external force.

A2 What is the effect?

A1 It will move continuously [It will never stop moving].

A2 But there is rain, which means there is an external force, automatically, the trolley will definitely stop. For example, [1]suppose that I push this trolley while it is raining [while pointing the trolley image on the given problem]. [2]I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, [3]so the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.

[. . .]

A4 Ooo, it will stop, why?

A2 Yes . . . Because if there is no external force action, it will continue to move. But if, for example, there is an external force, it will stop at a certain time.

H1 Yes, I agree [A1 agrees with A2] . . .

[. . .]

A4 Wait, if forces, not, kinetic energy [while writing a formula]

A2 $E_k = 1/2mv^2$

A1 Because of the mass increase.

A3 Yes, the mass increases.

[. . .]

A1 The speed is decreasing, right? Because initially the mass is small and the speed is higher, then the mass increases, so that means . . .

A3 So, it has an effect.

A1 Yes, it has an effect, the trolley will stop.

A4 Yes, at first it rolls continuously then this [indicates trolley] will be filled with water. Over time the speed becomes slower and slower, until maybe it stops.

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

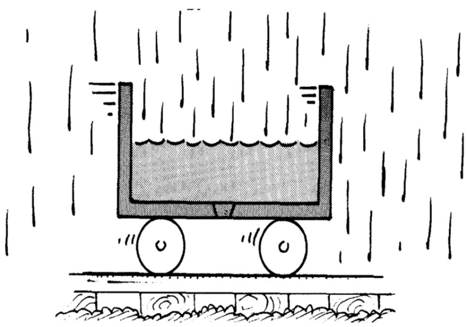

Fig. 2. (Color online) Illustration of Problem 1.

As can be seen, the words "*suppose that I push this trolley while it is raining*" were coded as an imagery indicator. It was the sign that participant was starting to visualize a TE. As expected, she visualized pushing the trolley and showed that by putting one of her hands on the trolley image on the given question. After the visualization step, A2 performed an experiment in her mind and then described the results of her TE that the mass of the trolley will increase and will stop at a certain time. A2 then shared her TE to group members so that it could be run and evaluated together. In such situations, there was a process of further discussion by students in their groups by asking and answering questions, supporting and clarifying arguments, validate the result of their TE, and so on. For example, A2 validated the result of the TE using Newton's first law. A1 also evaluated the results of the TE by using the kinetic energy equation: If, initially the mass of a trolley is small and it is moving at high speed, then when the mass increases due to the accumulated rainwater in the trolley, logically, its speed should decrease. Here, A1 used logic along with the kinetic energy equation (initial E_k = final E_k). This process of validating the TE was done continuously until the participants reached a conclusion as a collective agreement.

To encode the factors that trigger the emergence of TEs when students interact with each other in their groups, we used a data coding method suggested by Miles *et al.* [24] and Saldaña [30]. They divided data coding into two main stages: first cycle and second cycle. The first cycle coding is a way to initially summarize segments of data while the second cycle coding is a way of grouping those data summaries into categories or themes. Through this method, five core categories were grouped deductively as the factors for the emergence of the TEs: conflicting ideas, similar ideas, support from more experienced people, inspiration by bodily knowledge, and inspiration by imaginary visual knowledge.

We made an effort to increase validity by repeatedly checking using peer reviews. We also shared and discussed with two science education researchers who were invited independently. We invited them to separately identify the factors of TEs in the transcript of audio and video recordings. We discussed and classified them until around 92% agreement level was reached. We also provided opportunities for students to check whether the interpretation was distorted or not in order to improve the reliability of data analysis.

IV. Results and discussion

The data analysis identified five factors that trigger the emergence of TEs when students interact with each other in their groups to solve physics problems. The list and frequencies of factors that trigger the emergence of TEs are presented in Table 2.

As can be seen, students performed TEs not only because they were inspired by their own personal knowledge (bodily knowledge and imaginary visual knowledge) but also because of interaction among students in a group to solve a problem (conflicting ideas, similar ideas, and support from experienced people). The similarity of ideas is the most dominant factor that triggers the emergence of TEs and then followed by inspiration by body knowledge, conflicting ideas, inspiration by imaginary visual knowledge, and support from experienced people, respectively.

The results of this study support argument in the literature that both scientists and students use TEs as a cognitive tool for solving problems [7,18,22,27,29]. Table 2 shows that for the first problem, only one TE was produced by each group, while for the second problem, Groups 1 and 3 each produced three TEs, and Group 2 produced two TEs. This indicates that students used TEs as a cognitive tool in solving physics problems. As seen, there is some moment where students did more than one TEs for one physics problem which they faced. When students are given the opportunity to work together to solve meaningful problems, they perform TEs

Table 2. List and frequencies of factors that trigger the emergence of TEs.

Factors	Group/Problem (P)															Total
	Group 1					Group 2					Group 3					
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	
Conflicting ideas	*	**											*	*		5
Similar ideas		*	*		*				*		*	*	*			7
Support from experienced people							**									2
Inspiration by bodily knowledge					*	*		*		*		*			*	6
Inspiration by imaginary visual knowledge					*				*			*			*	4

and share them with their group members to be polished and validated as a collective effort to achieve mutual agreements. In fact, when they failed to provide evidence of the resulting TE, they did not hesitate to redesign a new TE. The conclusion generated through the TE is then applied as a solution to the physics problem.

Thus, when students are organized to work in a group, they have the opportunity to do more TEs than work independently. In a group, there are five factors that can encourage them to do TEs, whereas when learning independently, students doing TEs are only encouraged by their own personal knowledge factors. Students construct TEs not only for proving their assumptions but also for supporting their previous TEs or hypotheses that have been proposed as a solution to the problems. The following section discusses each category of the factors in detail.

1. Conflicting Ideas

During the data analysis, there was some evidence showing that TEs emerged due to differences in opinion between group members in understanding the problems. These differences encouraged group members to broaden their perspectives so that they try to build a TE to prove their ideas and simultaneously refute the ideas of their fellow group members. The following transcript is an example of a TE arising because of differences of opinion among the participants. The transcript was taken from the Group 1 problem-solving session transcript while working on Problem 1. The problem was asking about the possible effects of rain collecting in a trolley while the trolley was moving: "Suppose that a trolley is rolling without friction in a downpour where rain is falling vertically, and an appreciable amount of rain falls into the trolley and accumulates there. Consider the effect of the accumulating rain on the speed of the trolley."

R OK. Let's start from the first question . . . Now, imagine the possible effect of the accumulating rainwater on the trolley's speed as shown in the figure [Figure 2]. What do you think?

A4 Is the path a straight line?

A1 Is it pushed like this [while pushing the cellphone]?

R Yes, the path is a straight line. Yes, it is pushed. [. . .]

A1 So, I think that there is no external force and no friction.

A4 Aaa, external force.

A2 What is the effect?

A1 It will move continuously [It will never stop moving].

A2 But there is rain, which means there is an external force, automatically, the trolley will definitely stop. For example, 1suppose that I push this trolley while it is raining. [2]I push this trolley forward to roll on a straight road and the rain falls down vertically and hits it, [3]so the mass of this trolley will increase, so there is an external force, which means that the trolley will automatically stop at a certain time on the condition that the rainwater is being collected in the trolley.

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

In this episode, the words “suppose that I push this trolley while it is raining” (Line 9) were coded as an indicator of visualization. This indicated that A2 started to visualize a TE. As expected, she visualized pushing the trolley and showed that by putting one of her hands on the trolley image on the given question. She then performed an experiment in her mind, and described the results (Line 9). By using her mind’s eye, A2 saw that raindrops hit the trolley and being collected there, causing the mass of the trolley to increase (mass of trolley + rainwater collected). A2 then shared her TE with the group members so that it could be run and evaluated together.

However, before A2 started to visualize a TE, the participants first actively involved themselves in understanding the problem. At the beginning of the discourse, A1 and A4 asked the researcher to clarify the problem (Lines 2-3). After that, A1 assumed that there was neither external force nor friction force acting on the trolley (Line 5). A4 supported the assumption being built by A1 by saying, "Aaa, external force" (Line 6). However, A2 asked A1 and A4 what the effect of the external forces is. A1 then responded that the absence of external forces would allow the trolley to move continuously (Lines 7-8). In other words, A1 assumed that there is no effect of the accumulating rainwater on the trolley’s speed. Suddenly, A2 rejected the assumption built by A1 and A4, saying that rain hit the trolley, meaning that there is an external force acting on the trolley (Line 9). Due to the external force acting on the trolley, it will not move continuously, but will stop at a certain time. A2 then began to visualize a TE, using the words “suppose that” in order to prove her assumption and simultaneously refute A1’s and A4’s assumptions.

This discourse demonstrates that the conflicting ideas in understanding a problem can encourage participants to broaden their perspectives so that they are compelled to perform a TE in order to support their ideas and simultaneously reject the assumptions of their opponents. In physics, there are several examples of TEs that are similar to the case above where they are used by scientists to refute opposing ideas and simultaneously produce new ideas. Brown [4] called this kind of TE a platonic TE. Galileo’s free fall TE is an example that refuted Aristotle’s view that heavier objects fall faster and simultaneously established the new idea that all objects fall at the same speed. Thus, the conflict of ideas in understanding problems is one of the factors that can trigger the emergence of TEs.

2. Similar Ideas

TEs can also arise when two or more participants who have similar ideas are actively involved in constructing assumptions. There were several examples in this study where two or more participants jointly constructed assumptions, and then one of them carried out a TE to support their assumption. The following is an example where a TE arises under these conditions. The transcript is taken from Group 1’s work on Problem 5, as shown in the transcript excerpt below. The problem was asking about magnetic cars: “Imagine a U-shaped magnet fixed in front of a car. Will hanging another U-shaped magnet facing it with opposite poles make the car move? Why or why not?”

R Now we are going to the last question, Problem 5. . . So, do you think the car would move or not?

[. . .]

A2 Is the car initially at rest?

A1 Yes, the car is at rest, then someone brought the magnet closer to it.

A2 I think that if the model is like this picture [while pointing the picture on the given problem] then the car will move.

A1 Yes, I think so.

A2 Except the hanging magnet has the same magnetic force as the one in the car.

A1 Because it could be that the hanging magnet will be pulled by the magnet in the car.

A2 So, maybe it depends on how strong the magnetic force is. If these two magnets have the same magnetic force, the car will not move, right?

A1 Yes, maybe.

A2 Yes, for example, [1]try to imagine, [2]if you [A1] are in the car with a magnet fixed in front of it, then you hold another magnet like in the picture from the given problem [A2] uses hand to demonstrate]. If the model is like that, then [3]the car will not move, instead it may be a hanging magnet will move towards the car.

A1 Yes, because there is additional mass in the magnet fixed to the car

A2 Yes, because the force here [pointing the hanging magnet] is smaller . . .

A3 What force do you mean?

A1 I think his intention [indicating A2] is the magnitude of the magnetic force on the hanging magnet. So when the hanging magnet is brought close to the magnet in the car, the car will not move because of the masses of the car and person attached to it. So, we think that the hanging magnet cannot make the car move.

A2 Yes, I think it is logical if the situation is like it is in the picture [pointing to the problem given].

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

At the beginning of the discourse, it is clearly seen that A1 and A2 jointly built the assumptions used as the basis for solving the problem at hand (Lines 2-9). They responded to and supported each other. To further strengthen their ideas that the car would not move, A2 did a TE (Line 10) using the words "try to imagine" (as an indicator of visualization). In her experiment, A2 imagined that if A1 brought a U-shaped magnet closer to another U-shaped magnet attached to the car (assuming the car would move) then perhaps the magnet held by A1 would be attracted to the magnet in the car. Thus, according to A2, the car will not move. The results of this TE were supported directly by A1, who suggested that the magnet in the car has extra force (the extra mass of the car and the person) that the hanging U-shaped magnet does not have. Therefore, A1 and A2 suggest that the hanging U-shaped magnet does not have a force strong enough to make the car move because the magnets have the same magnetic force (Lines 7-8) and the U-shaped magnet on the car has extra force (Lines 11-14).

Unlike the previous factors (conflict of ideas), this TE arises when the participants have similar ideas. The similarity of ideas encouraged participants to do a TE to further support their assumptions. This corresponds to the function of TEs as cognitive tools used by scientists in developing and supporting their theories [12,13]. Thus, it can be said that the similarity of ideas in building an assumption or hypothesis is one of the factors that can trigger the emergence of TEs.

3. Support from experienced people

Another factor that can encourage the emergence of TEs while participants are interacting in small groups to solve physics problems is the support from more experienced people. In this study, one group consisted of some participants who were master's students and some who were undergraduate students, and it was noticeable that undergraduate students were able to perform TEs because of the support and guidance from the master's students. This support can be in the form of positive responses and also emotional support, such as facial expressions and hand gestures. The following is an example where an undergraduate student did a TE because she got support and guidance from master's students. The transcript was taken from Group 2's response to Problem 2, as shown in the transcript excerpt below. The problem was asking about which scientist can detect her own motion in space, the scientist who is in the box moving in a straight line or the scientist in the smoothly spinning box: "A scientist is completely isolated inside a smoothly moving box that travels a straight-line path through space, and another scientist is completely isolated in another box that is spinning smoothly in space. Each scientist may have all the scientific goodies she likes in her box for the purpose of detecting her motion in space. Which scientist can detect her motion in the space?"

R We continue on to Problem 2 . . . Now, which scientist can detect her motion?

[. . .]

B1 In my opinion, the scientist who feels that she is moving is the scientist in the smoothly spinning box . . . Meanwhile, the scientist in the box moving in a straight line will not feel that she is moving. I think it is the same if we are on a ship. How about you guys [pointing to undergraduate students]

B3 Maybe this one [pointing the spinning box]

B4 Yes, maybe the spinning one because if we are on the airplane.

B1 The spinning box, why?

B4 Because if we are on an airplane . . .

[These photos show the situation right before B4 did TE. B4 seems to feel embarrassed to start doing a visualization of TE. Shortly before B4 started to visualize the TE, B4 and B3 laughed several times, glanced at each other, and B4 lowered her face to the table. B4 took about 1 minute to start visualizing the TE when asked by B1.]

B1 Yes, what happens if we are on an airplane? Do not be shy, just speak up.

B4 That is the same thing as you [B1] said when we are on a ship.

B1 Yes, can you imagine that we are on a ship?

B4 Yes, I try to replace a ship with airplane so that it is easy. [1]Try to imagine that we are on an airplane that moves in a straight line and at a constant speed without any friction. [2]If I drop a coin into a glass, 3that coin will go into the glass, right?

B2 Yes, I think it's the same if we are on a plane with this one [pointing at the box moving in a straight line].

B1 Yes, I think so too.

B4 Ahh··· then 1if, for example, when we are on a roller coaster. If we are on a roller coaster and [2]try to drop a coin into a glass, [3]hen it is difficult, so, we will keep feeling like we are moving, won't we?

B2 Roller coaster?

B1 Carnival swings, maybe.

B4 Something that moves like this [while spinning her hand], right? When we are on it, can you feel that you are moving?

B1 Yes, sure.

B2 Yes, we can feel it.

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

At the beginning of the discourse, B1 responded to the problem given by saying that the scientist who is pushed forward will not feel that she is moving because the situation is the same as that of people on a ship (Line 2). B1 then asked B3's and B4's opinions, and they also agreed that the scientist in the box who was pushed forward did not feel that she was moving. However, to prove this claim, the two undergraduate students felt ashamed about explaining their opinions. Several times they laughed before starting to do a TE, and B4 even lowered her face to the table (Line 6). In this condition, B1 as a master's student tried to encourage and support B4 to express her opinion (Line 7). B4 then did a TE using the ideas expressed earlier by B1 (people on a ship), but she replaced the imaginary ship with an imaginary airplane (Lines 8-10).

The results of B4's TE were then responded to positively by B1 and B2 (Lines 11-12). With this support, B4 then continued to do TE for different situations in order to describe the situation that occurs for a scientist who is in a rotating box (Line 13). Afterward, the participants began to run, evaluate, and fix their TE until they reached a mutual agreement (Lines 14-18). This demonstrates that the guidance and support of experienced people is an important factor that can encourage the emergence of TEs.

4. Bodily knowledge

TEs can also arise when participants interact in a group to solve physics problems because they are inspired by their bodily knowledge. According to Reiner and Gilbert [29], "bodily knowledge rises from physical

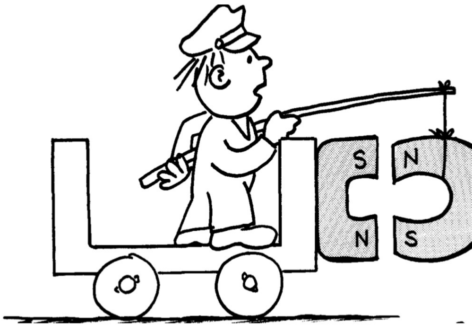

Fig. 3. (Color online) Illustration of Problem 5.

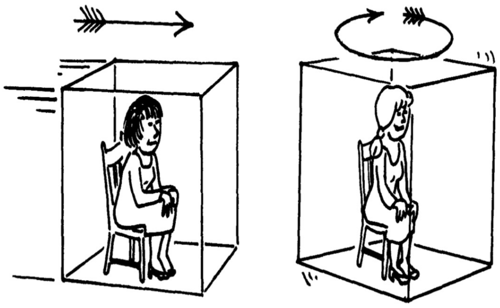

Fig. 4. (Color online) Illustration of Problem 2.

experiences, such as riding bikes or playing basketball and provides us with tacit knowledge about the dynamics of objects and motor performance" (p. 490). The knowledge embodied in perceptual-motor intuition is often used not only by students but also by experts when they are solving a problem [6], and it can be reflected in their motor and kinesthetic actions [29].

During the data analysis, there was some evidence that participants begin visualizing a TE because they are inspired their physical experiences that are similar to the physics problems they are faced with. The following is an example of participant visualizing a TE because it was inspired by his bodily knowledge. The following transcript was taken from the problem-solving session when Group 2 was responding to Problem 5 (see Figure 3)

R Now, we are going to the last question. So, what do you think is the solution to this problem?

[. . .]

B1 Ok. In my opinion, the car would move on the condition that the hanging magnet has a greater magnetic force so that it could move the car. ⋯ Try to remember when we were kids and playing with magnets. [1]Imagine that we are playing with magnets. [2]If the magnets, usually put on the table, if one of the magnets is pulled in this way [B1 demonstrates as if putting one magnet closer to another magnet] [3]then the other magnet will be attracted. ⋯

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

As can be seen, B1 started visualizing a TE because he had experience as a child playing with magnets (Line 2). B1's physical experience of playing with magnets encouraged him to perform a TE in order to solve the problems he was facing. The words "imagine that we are playing with magnets" are coded as an imagery indicator, which indicates that B1 started to visualize a TE (Line 2). While performing the TE, B1 demonstrated using both hands as if bringing the first magnet closer to the second magnet, with the second magnet being attracted to the first magnet. This demonstrates that bodily knowledge can be an important factor that can encourage the emergence of TEs.

5. Imaginary visual knowledge

The last factor that can encourage the emergence of TEs is participants' imaginary visual knowledge. Unlike bodily knowledge, this knowledge is not inspired by physical experience but instead refers to individual abilities in imagistic simulation, such as manipulation of imaginary objects and imagined situations [29].

The data analysis showed evidence that participants began visualizing TEs because they were inspired by their own imaginary visual knowledge. In general, participants who are in this state perform a TE to predict the answer to the problem given. When researcher finished reading the problem, they immediately visualized the imaginary world by manipulating imagined objects and situations. The transcript below was taken when Group 3 was responding to Problem 2 (see Figure 4) is an example of this condition.

R We continue on to Problem 2 . . . So, what do you think about this problem? Which scientist can detect her motion?

[. . .]

C4 Aha··· [1]Imagine when we are inside a train that is traveling at a high and constant speed. For example, on a train that is moving straight forward and has no windows, so we cannot see outside. At that time, we do not know whether we are moving or not. [2]If we drop a coin into a glass, [3]the coin will surely go into the glass, right? [1]If for instance, the thing we are on is spinning, like a propeller, and [2]we try to drop a coin [into a glass], [3]then it will be more difficult to drop the coin right into the glass, right?

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1 = visualize imaginary world; 2 = perform experiment; 3 = describe the results

After participants discussed the problem for a while, C4 had an idea for solving the problem and said “aha” (Line 2). She then created an imaginary world by manipulating the object (in the problem given, the object is a scientist in a box, while in C4’s TE, the objects are a train, a glass, and a coin). C4 then constructs a situation where she is on a fast train moving at a constant speed on a straight road with no turns. Also, the train has no windows so outside the train cannot be seen. With this situation, C4 then did an experiment, dropping a coin into a glass and seeing that the coin fell right into the glass. She then imagined another situation where she was on the something spinning and trying to drop a coin into a glass and found that getting the coin in was very difficult. Afterward, C4 shared her TE with the group members to be run and evaluated together.

Based on this discourse, C4 started to perform a TE to predict the answer to the problem given. She did the TE not because she was inspired by her experience or because there were different or similar ideas in the group but because she was inspired by her imaginary visual abilities. She first manipulated imaginary objects and conditions to start doing a TE. This demonstrates that imaginary visual knowledge is an important factor that can encourage the emergence of a TE.

V. Conclusion and Implications

It can be concluded that there are five factors that trigger the emergence of TEs when students interact with each other in their groups to solve problems. First, conflicting ideas between students in understanding a problem can encourage them to broaden their perspectives so that they are compelled to do a TE in order to refute the assumptions of their fellow group members. Second, the similarity of ideas in building an assumption or hypothesis also can encourage students to do a TE to further support their assumptions. Third, the guidance and support of more experienced students can also encourage less experienced students (in this case master’s students and undergraduate students) to visualize TE so that the TEs can occur. Fourth, students’ bodily knowledge is also considered an important factor that can encourage the emergence of TEs, in that students’ physical experience that may be similar to the physics problems with which they faced. Last, students’ imaginary visual knowledge, which refers to individual abilities of imagistic simulation, such as the manipulation of imaginary objects and imagined situations, can also encourage the emergence of TEs.

The results of this study support argument in the literature that TEs are a cognitive tool that both experts and students can use to work on problems [7,18,22,27,29]. Although some researchers argued that TEs do not need to be built together because students can independently produce novel scenarios, make predictions, and evaluate their own scenarios [32], this study has shown that students performed TEs not only because of their own personal knowledge but also because of interaction between students in a group. Therefore, when students are organized to work in a group, they have the opportunity to do more TEs than work independently. In a group, there are five factors that can encourage them to do TEs, whereas when learning independently, students doing TEs are only encouraged by their own personal knowledge factors. TEs are used by students not only to prove or evaluate their assumptions but also to support their hypotheses or previous TEs in order to find solutions to the given problem. In other words, by interacting with others, students have opportunity to share and criticize ideas, support each other, broaden their perspectives so that they are encouraged to do TEs in order to solve the problems which they faced. Conflicting ideas between students in understanding a problem encourage them to perform TEs in order to support their ideas and simultaneously refute the ideas of their fellow group members. Likewise, sharing similar ideas can lead to students responding to and supporting each other, and performing TEs in order to further support their assumptions. This is in accordance with the function of TEs as an imagination tool for scientists not only to refute theories [19] but also to develop and support existing theories [12,13].

Although some researchers have recommended using TEs in teaching physics [1,2,12], recommendations for physics teachers on how to apply them in meaningful ways and how to help students find effective thinking procedures in running TEs are still rare. Moreover, several studies have also shown that students have difficulty in constructing TEs independently [1,5,18] and, therefore, we think that placing students into group learning is the most effective way to encourage students to perform TEs rather than independently. There are many benefits that can be obtained by placing students in a group to construct TEs. For example, in group learning, students have the chance to discuss, share ideas, support each other and also use each other's resources and skills (e.g. experience, knowledge, and logic) so that students who have difficulties in constructing TEs will be helped by other students. Also, it can improve social interactions and support diversity. In group learning, students must work together with different backgrounds, experiences, cultures, and knowledge. When students spend time together to work, they will learn how to relate to each other. They also make friends by getting to know each other, thus increasing morale and group performance.

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