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Semi-Discovery Learning Support System for Analogical Reasoning in High-School Physics

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Abstract: In this paper, we describe a learning support system that supports the learning process by combining the processes of analogical reasoning and discovery learning. In learning high-school physics, as a method to deepen the understanding of physical phenomena, learners focus on mapping knowledge for known phenomenon and target phenomenon. This similarities-based mapping of knowledge enables learners to discover the type of influence between the knowledge parameters. However, before learners focus on the similarities, they must develop correct hypotheses for each phenomenon. Moreover, it is difficult for learners to create/modify/justify their hypotheses. In addition, they sometimes struggle to discover similarities in these phenomena. Our proposed system provides such learners support functions to complete the learning process. For our preliminary evaluation, nine participants completed pre- and post-test questionnaires using the proposed system. The results revealed that the system helped learners identify the relationships among parameters and similarities/differences among phenomena. However, the system did not help learners who could not identify the appropriate formula by viewing the graph. Therefore, future studies should focus on the needs of such learners and provide inputs to improve the system.

Keywords: Discovery learning, analogical reasoning, tutoring system, high-school physics

1. Introduction

Analogical reasoning is a thinking method to acquire new knowledge (hereinafter: target knowledge, TK) by applying known knowledge (hereinafter: base knowledge, BK) to new problems and situations. In this method, it is necessary to choose appropriate BK for TK, based on the semantic/structural similarities between the BK and TK. Numerous studies have indicated the importance of analogical reasoning in education and have reported application cases in some areas (Gadgil, Nokes-Malach, & Chi, 2012; Jee et al., 2010; Kurtz & Gentner, 2013). Day and Hills (2010) indicated that analogical comparisons used not only similarities but also differences between BK and TK.

As for high school physics, to deepen the understanding of physical phenomena via analogical reasoning, learners focus on the behavior of phenomena of BK/TK and the relationships among the parameters of these phenomena. Subsequently, the learners discover the type of influence of parameters by changing some parameters. In the cases of vertical spring and simple pendulum movements, learners observe these phenomena via T-k graph and T-m graph for BK and T-g graph and T-l graph for TK. While changing parameters in these phenomena, learners discover the relationships between parameter m and l, and K and g.

Base Knowledge: Vertical Spring Pendulum Movement

Formula: $\mathrm{T} = 2\pi\sqrt{\frac{m}{k}}\ T: cycle, m: mass, k: spring\ constant$

Graphs: T-k graph and T-m graph

Target Knowledge: Simple Pendulum Movement

Formula: $\mathrm{T} = 2\pi\sqrt{\frac{l}{g}}\ T: cycle, l: lengh\ of\ code, g: gravity$

Graphs: T-g graph and T-l graph

Relationships among parameters: m and l, K and g

Therefore, in this study, a learning process that combines the processes of analogical reasoning and discovery learning was employed. Discovery learning is a learning method wherein learners acquire knowledge by repeatedly creating and verifying hypotheses based on their observations. In discovery learning, learners can discover the relevance of phenomena through their trials and errors. However, in experiment-based discovery learning, learners are required to collect substantial data by changing input and situation parameters. Moreover, if the parameters to be observed are invisible, it is difficult for learners to observe the influence of the other changed parameters. In addition, learners struggle to create and verify hypotheses based on observations.

Some studies have focused on simulating and visualizing physical phenomena for education (Jose, Akshay, & Bhavani, 2014; Kaufmann & Meyer, 2008; Nancheva & Stoyanov, 2005); however, the simulators in theses do not provide sufficient support to struggling learners to develop their own hypotheses. Horiguchi, Hirashima, and Forbus (2012) suggested an error-based simulation that visually displays learners' incorrect formula, enabling them to identify errors by observing the visualization. Takeuchi (2000) suggested an intelligent tutoring system that allows learners to apply the knowledge acquired from a simple problem situation to a complicated problem situation; however, this tutoring system does not support the application of knowledge to different phenomena.

In this study, we focused on the learning of high-school physics. We proposed semi-discovery learning process wherein a system supports learners to create/verify/justify their hypotheses to reduce difficulties. The proposed system provides a virtual laboratory that can not only simulate and visualize phenomena but also generate graphs for the relationships between parameters. In addition, the system enables learners to identify the type of influence of the parameters by changing some parameters, thereby increasing focus on the similarities and differences between the BK/TK. In this paper, we describe the semi-discovery learning process with our supporting system and evaluate whether the system enables learners to (i) resolve the problem, (ii) understand the relationships among parameters, and (iii) identify the similarities and differences between BK and TK.

2. Semi-Discovery Learning for High-School Physics

2.1 Learning Process in Semi-Discovery Learning

The proposed semi-discovery learning process combines analogical reasoning, which comprises four steps: (1) selecting the BK, (2) mapping the BK and TK, (3) verifying the mapping, and (4) identifying the similarities/differences, and discovery learning, wherein learners acquire a rule system by iterating hypotheses verification. In physics, learners can acquire a model for phenomena by identifying the relationships among the parameters of the phenomena. For instance, a model of "Equations of motion" is $\vec{F} = m\vec{a}$; learners who have acquired the model and relationships among the parameters can attempt to apply the same structure into other phenomena. Consequently, they can acquire relationships between BK and TK through these trials. However, some learners face difficulties in identifying the relationships among the parameters. Therefore, the proposed semi-discovery learning process is simplified by a learning support system. Figure 1 displays our framework for the semi-discovery learning process comprising the following two steps.

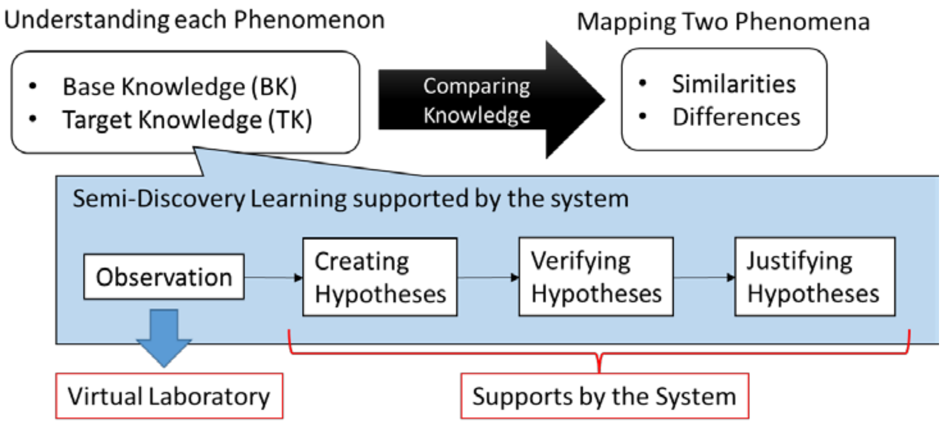

Figure 1. Analogical reasoning via semi-discovery learning

1. Understanding each phenomenon

Learners learn phenomena through discovery learning processes: observation, development, verification, and updating of hypotheses. The proposed system suggests phenomena parameters that the learners should focus on. Subsequently, the learners observe the changes in the parameters of the phenomena in our system's virtual laboratory. Thereafter, they develop a hypothesis that appropriately describes the relationships among parameters. The system generates graphs and formulas based on their hypotheses, and the learners compare the graphs and formulas with the real phenomena. Thus, through a continuous cyclical process, the learners verify and update their hypotheses.

2. Mapping two phenomena

After obtaining all graphs and formulas based on the BK and TK, the learners map them. In particular, they understand the similarities between the BK and TK by identifying common parameters. Subsequently, the learners clarify the differences between two phenomena based on the similarities.

2.2 Supporting Functions for Semi-Discovery Learning

To realize a framework for semi-discovery learning in physics, the supporting system should perform the following functions.

(a) Virtual Laboratory

In discovery learning, learners should be able to observe the changes in phenomena with changes in the parameters. Furthermore, in addition to highlighting the visible aspects, the system should display the invisible aspects (e.g., speed).

(b) Automatic Graph Drawing

Although it is important to summarize the input/output results of formulas, it is difficult to collect the input/output for the BK/TK, and learners often struggle. Therefore, the system should automatically generate graphs and parameters.

(c) Templates for Formulas

Novice learners generally face difficulties in developing hypotheses using formulas from the very beginning. Therefore, the system should provide templates based on formulas from high-school physics textbooks.

(d) Graph Feature Analysis

The system should inform the learners about the differences between their hypotheses and the correct phenomena through a graphical representation of learners' hypotheses and the correct formula. In addition, the system should highlight the following differences in the graphs.

- Differences in the slopes.
- Whether the slope passes through the origin.

- Mathematical differences (modulus, absolute values, exponent, log, and square roots) in the formulas.

(e) Advisement

In discovery learning processes, learners typically struggle with identifying the errors in their hypotheses and are unable to update their hypotheses to rectify the errors. Therefore, to support such learners, the system should provide suggestions that highlight the errors in the learners' hypotheses and what type of knowledge is required to update the hypotheses. The proposed system supports the following advisements.

- Differences in the features of the graphs.
- Differences in the parameters of the graphs.

2.3 Supporting Strategies

Step 1. Observing the BK and TK

The virtual laboratory displays animations of the phenomena for learners to observe the movement of the phenomena; for instance, the display of the vertical sprint pendulum movement.

Step 2. Acquiring the BK and TK

In Step 2, the learners create hypotheses using the graphs and model formulas to develop formulas and identify relationships among the parameters of BK/TK.

Step 2.1. Developing hypotheses

- Hypotheses of the graphs

The system automatically generates sample graphs with appropriate types and ranges of parameters. The learners select a suitable graph from these sample graphs to develop their hypotheses. For instance, the system generates T-k graph and T-m graph for the BK.

- Hypotheses of the formulas

The learners select a suitable formula template from those provided by the system. Thereafter, they operate the parameters and constants in the template.

Step 2.2. Confirming hypotheses

- Hypotheses of the graphs

The learners confirm their hypotheses by comparing the hypothesized and correct graphs in the BK/TK

- Hypotheses of the formulas

The learners confirm their hypotheses by comparing the hypothesized and correct formula graphs in the BK. In addition, the system indicates the difference between these graphs.

Step 2.3. Justifying the hypotheses

The learners who identify the errors in their hypotheses repeat Step 2.1. Thereafter, they create updated hypotheses of graphs and formulas.

Step 3. Identifying the similarities in the parameters of the BK and TK

Prior to this step, the learners have acquired the models and graphs of the BK and TK. Thus, the learners are prepared to identify the similar parameters to derive a variable. For instance, T is derived based on k in the BK and g in the TK. The system displays alternative graphs of the BK and TK; the learners choose two similar graphs from these alternative graphs.

Step 4. Identifying the differences in the parameters of the BK and TK

The learners choose appropriate differences from the following alternatives.

The types of the differences:

(1) Parameters of the phenomena.
(2) Type of devices realizing the phenomena.
(3) Increasing the number of devices realizing the phenomena.
(4) Decreasing the number of devices realizing the phenomena.

(5) Perspectives that require the learners' attention, such as mechanics, electromagnetics, and atomic science.
(6) Parameter ranges of the phenomena.
(7) Variables in the BK and constants in the TK perform the same functions.
(8) Constants in the BK and variables in the TK perform the same functions.

3. System Overview

3.1 Databases

The system has three databases (DB): Phenomena DB, Mapping DB, and Templates DB. The Phenomena DB defines formulas, relationships among parameters, and type of graphs for each phenomenon. The Mapping DB defines similarities and differences between the BK and TK. The Templates DB defines formula templates that learners use in creating their formula hypotheses.

3.2 System Interface

Figure 2 presents the main interface of the system. The interface has phenomena animation areas for the BK and TK to observe similarities and differences in their parameters. The concept-mapping table indicates similarities, differences, and types of differences between the BK and TK; these items indicate that the learners learned in the process. In addition, the system displays the number of rest relationships that learners should discover to highlight their progress. The bottom of this interface has three buttons for the BK and TK: go to virtual laboratory, reset the simulation, and create hypotheses.

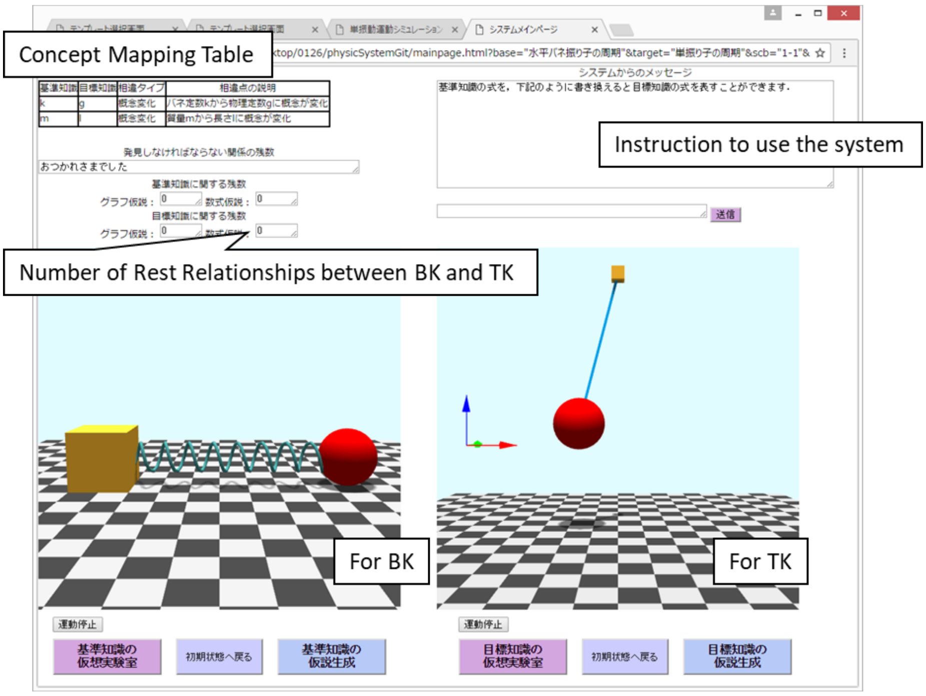

Figure 2. Main interface of the system

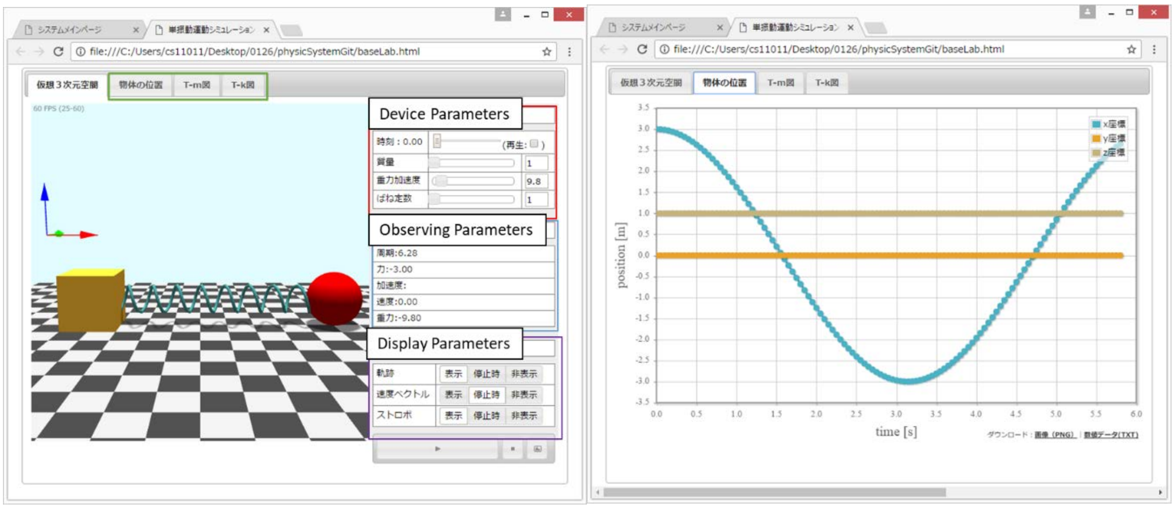

Figure 3. Interface of Virtual Laboratory.

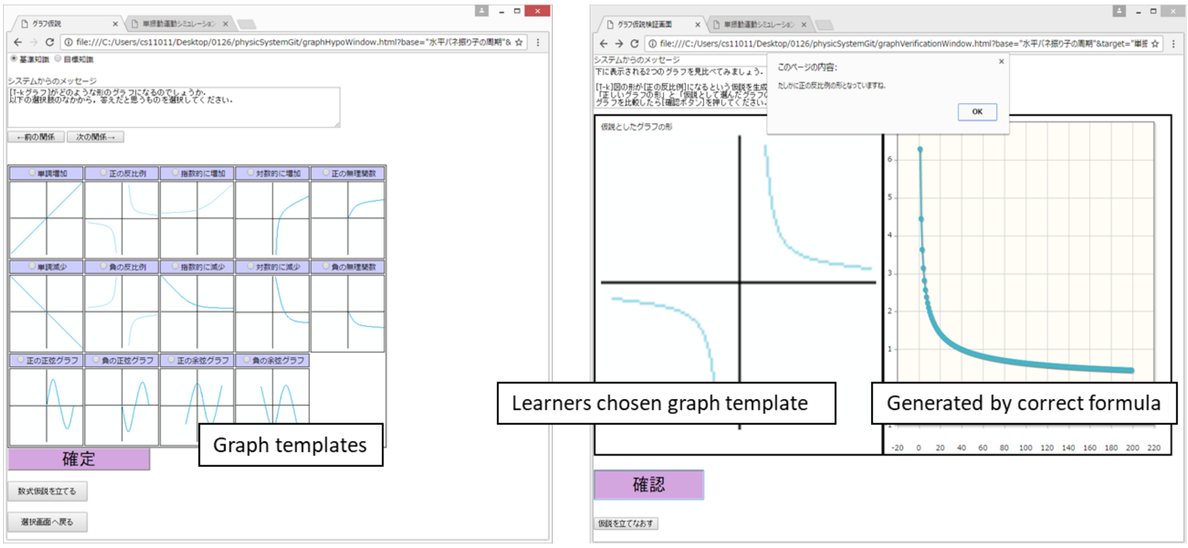

Figure 4. Interface for creating graph hypotheses.

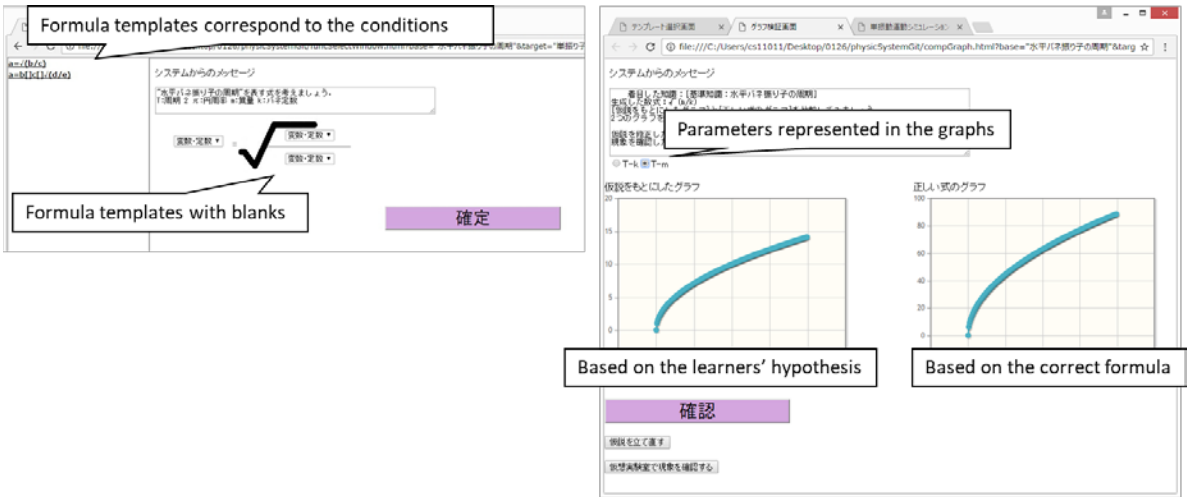

Figure 5. Interface for creating formula hypotheses.

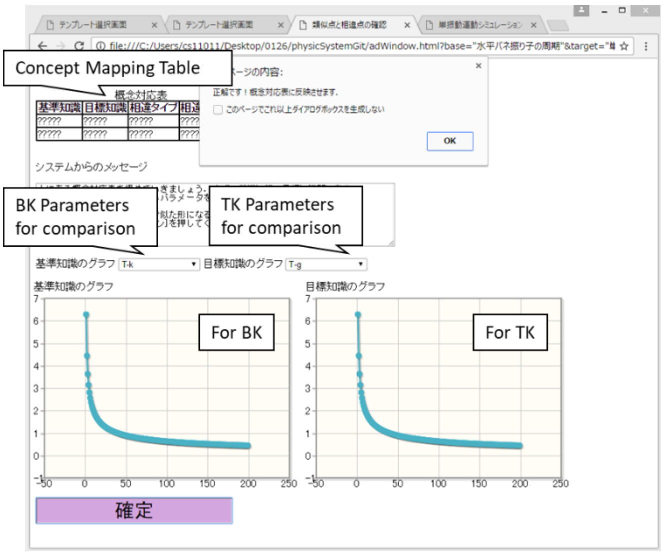

Figure 6. Interface for finding similarities and differences between BK and TK.

Figure 3 shows the interface of the Virtual Laboratory, developed using physics.js (Natural Science, 2017; Endo, 2015). Learners can change the parameters of the devices in the device parameters area and observe the values of the parameters simulated by the device parameters. In addition, the system prepares some tabs for appropriate types of graphs based on the BK and TK. When learners click on the tabs, the system generates graphs calculated on the basis of the device parameters.

Figure 4 shows the interface for learners to create graph hypotheses. Learners select an appropriate graph form to represent the relationship between the parameters. The system suggests 14 types of graph templates. When the learners select a graph, the system displays the selected graph and the graph generated by the correct formula in the situation. Learners validate their graph hypotheses by comparing the two graphs.

Figure 5 shows the interface for learners to create formula hypotheses. At first, learners select the appropriate formula template based on the elements (e.g., a radical sign, a fraction, a modulus, and other frequently used elements) including/excluding their formula hypotheses. The left tab in Figure 5 presents two formula templates that correspond with the conditions. Learners choose the appropriate formula and set appropriate variables/constants in the situation. Subsequently, the system generates two graphs: one using the learners' formula and the other using the correct formula in the situation. Learners validate their formula hypotheses by comparing the two graphs.

Figure 6 shows the interface for identifying similarities and differences between the BK and TK. If learners create the correct graph and formula hypotheses for the BK and TK, the system redirects to this interface. In this interface, learners can choose relationships between the parameters of the BK and TK. The system displays the graphs for the parameters, and suggests learners to identify the similar graphs between the BK and TK. If the learners choose the similar graphs of the BK and TK, the system updates the concept-mapping table for the parameters used in the graphs as working similar in the BK and TK. Thereafter, the system suggests learners to choose the differences in the similarities from eight types of candidates mentioned in section 2.3. If the learners can choose the correct type, the system updates the concept-mapping table.

4. Evaluation Experiment

4.1 Hypotheses and Evaluation Process

We proposed the following three hypotheses:
H1: The system enables learners to complete the problems.
H2: The system enables learners to understand the relationships among the parameters of each phenomenon.
H3: The system enables learners to understand the similarities and/or differences among phenomena.

A total of nine university students participated in the preliminary evaluation of the system. We analyzed the differences between the participants using the proposed system and those using only the virtual experimental laboratory based on physics.js (hereinafter PHYSICS). A pre- and post-questionnaire was given to the participants. We defined the test administered to the participants after using PHYSICS as the pre-test, and that after using the proposed system as the post-test. Thereafter, we counted the blank responses in the pre-test based on the respective learning environment (i.e., the proposed system or PHYSICS). Because the form of the graph depended on the formula representing a phenomenon, we presented the participants with some problems about the formula representing the BK or TK and relationships among parameters. In addition, to analyze whether the participants could identify the similar parameters in the BK and TK, we presented them with some problems to identify the type of similar parameters in each phenomena and the type of difference among the combinations.

We prepared the following types of problems for the pre- and post-test.

- Relationships among parameters in the BK
- Formula representing the TK
- Relationships among the parameters in the TK
- Similarities among the combination of parameters
- Differences among the combination of parameters

Table 1 presents the steps, and the time taken to complete each step in the evaluation process.

Table 1: Evaluation process

	Step (min)	Summary
1	Pre-questionnaire (3)	Check the participants' educational history of physics. Check whether the participants can write formulas for the target phenomena.
2	Instructions (5)	Explain the interface of the proposed system to the participants.
3	Exercises using PHYSICS (30)	The participants complete exercises using PHYSICS.
4	Tutorial (15)	A tutorial on the interface of the proposed system with exercises on topics that many of the participants stated that they could solve in the pre-questionnaire.
5	Pre-test (10)	Check the results of step 3.
6	Exercises using the proposed system (30)	The participants complete exercises using the proposed system.
7	Post-test (10)	Check the results of step 6.
8	Post-questionnaire	The participants respond to questions regarding the learning support systems after using them.

Finally, we compared the pre- and post-test responses of the participants to validate the aforementioned three hypotheses.

4.2 Results

In the pre-questionnaire, all of the participants responded that they had learned physics in their high school.

Regarding H1, the average number of blanks responses in the post-test showed a 2.56 decrease from that of the pre-test (Table 2). Thus, the participants acquired some kind of knowledge about phenomena without facing any severe struggle in completing the exercise using the proposed system; perhaps, the participants had a real feeling of acquiring knowledge from the exercise. However, this did not imply that the learners acquired the correct knowledge. Therefore, we discussed the contents of their responses to validate H2.

Table 2. Number of blank responses in the pre- and post-test.

	Pre-test	Post-test
Formula representing BK	3	0
Relationships among parameters in BK	2	0
Formula representing TK	6	1
Relationships among parameters in TK	4	1
Similarity among the combination of parameters	6	1
Difference among the combination of parameters	6	1
Total	27	4
Average (per participant)	3.0	0.44

Table 3. Number of correct responses in the pre- and post-test.

		Pre-test	Post-test	Difference	Average
(A)	Relationships among parameters in BK	1	9	8	0.89
	Relationships among parameters in TK	0	8	8	0.89
(B)	Formula representing BK	1	7	6	0.67
	Formula representing TK	0	8	8	0.89
(C)	Similarity among the combination of parameters	0	8	8	0.89
	Difference among the combination of parameters	0	5	5	0.56
Total		2	45	43	4.78

Row (A) in Table 2 indicates that the number of correct responses for the relationships among the parameters in both the BK and TK increased to 8 (0.89 per participant on average) in the post-test. Row (B) in Table 2 suggests that the average number of correct responses for the formula representing BK increased to 6 (0.67 per participant on average) in the post-test that of the formula representing TK increased to 8 (0.89 per participant on average). Thus, an increasing for correct responses was observed. However, there were two participants who did not provide the correct formula representing BK. One of them used the proposed method and although the pre-questionnaire response was not correct, this participant acquired a part of the correct formula for the exercise using the proposed system. The other participant could not complete the exercise; this participant acquired the correct graph between parameters in the BK but could not identify the structure of the formula from the features of the graph. The system notifies learners of their incorrect hypothesis for a formula and after the learners accept the notification, it provides a graph and a table, listing the formulas used to create the graph. Although the participant used this function, the participant struggled, and therefore we could not confirm the effectiveness of the function. Thus, H2 is confirmed by the result that correct responses per participant in the post-test increased to 43 (4.77 per subject on average) from the pre-test. In addition, this indicates that the system does not provide sufficient support to learners who cannot guess the appropriate formula from the form of graphs

According to row (C) in Table 3, the correct responses about similarities increased to 8 (0.89 per participant on average) in the post-test. All participants who answered correctly completed the exercise using the proposed system; thus, the system enables learners to understand the common/similar parameters among phenomena. The correct responses about differences increased to 5 (0.56 per participant on average), which is relatively low compared with the increase in similarities responses. Thus, this preliminary evaluation validates H3.

5. Conclusion

In this paper, we proposed a semi-discovery learning support system for learning high-school physics. The system supports that learners understand similarities and differences in phenomena. It provides virtual laboratory, automatic drawing function, and other functions for creating/verifying/justifying learners' hypotheses. In our evaluation with nine subjects, our proposed system was useful for learners to identify the relationships among parameters and similarities/differences among phenomena. However, the results indicated that the supports of the system were not sufficient for learners who could not guess the appropriate formula from the form of graphs. Future studies should perform an in-depth analysis of such learners and update the design of semi-discovery learning using a support system.

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