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Analysis of Learning Activities with Automated Auxiliary Problem Presentation for Breaking Learner Impasses in Physics Error-based Simulations

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Abstract: Error-based Simulation (EBS) is a framework that supports learning by visualizing errors. EBS systems generate and visualize simulations of assumed phenomena from learner answers. By letting the learner observe the results, the system shows how wrong answers result in wrong phenomena. The system thus supports trial-and-error processes until a correct response results in correct phenomena. EBS systems effectively support trial-and-error in learning of physical mechanics. Despite this, learners may become stuck because the EBS system does not provide the correct answers to problems. Stepwise presentation of auxiliary problems can be useful for resolving such impasses. Auxiliary problems are simplifications of the original problem containing fewer targeted learning concepts, a scaffolding approach leading toward the original problem. Therefore, we developed a learning support system that adaptively presents auxiliary problems by determining from error trends the concepts that the learner does not yet understand. We also evaluated the developed system through experimentation. Using system logs from those experiments, we analyzed in detail the learning activities related to the auxiliary problem presentation function in EBS. The results suggested that adaptively presenting auxiliary problems to learners can effectively resolve impasses.

Keywords: Auxiliary problem, Error-based Simulation, mechanics learning, system log analysis

1. Introduction

Learning support systems with Error-based Simulation (EBS) provide effective environments for learning physical mechanics. EBS is a framework that supports learning by visualizing errors (Hirashima, Horiguchi, Kashihara & Toyoda, 1998), which has been demonstrated as effective in learning domains such as mathematics (Kurokawa, Tomoto, Horiguchi & Hirashima, 2018), English writing (Kunichika, Takeuchi & Hirashima, 2003), and physics (Hirashima et al., 1998; Ueno, Tomoto, Horiguchi & Hirashima, 2019). EBS systems generate and visualize simulations of assumed phenomena from learner answers. By letting the learner observe the results, the system shows how wrong answers result in wrong phenomena. The system thus supports trial-and-error processes until a correct response results in correct phenomena.

EBS is also effective for learning physical mechanics. However, some factors in EBS learning can result in impasses. One such factor is that EBS does not present correct answers because the aim of EBS is to induce a trial-and-error process. Another factor is that in some cases it is difficult to visualize errors from simulations. In the case of two vertically stacked objects, for example, if learners input a gravity force and a normal force for each object, those forces will be in equilibrium in the simulation (Figure 1). In this case, the system cannot visualize the error of a deficiency of force from the upper object pushing on the lower object. To address this factor, Ueno et al. (2019) developed an EBS system that provides measurement tools for visualizing error in indiscernible parameters such as load and velocity.

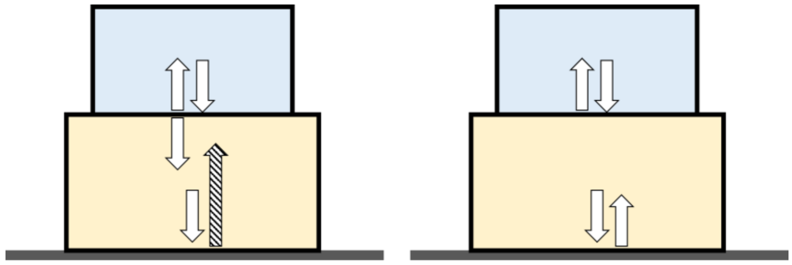


Figure 1. Case of difficult to visualize errors from simulations.

However, if the learner does not notice any errors while observing the simulation, they may not be able to resolve the impasse even with such support. We therefore focused on the presentation of auxiliary problems as one method for resolving learner impasses (Hirashima, Kashihara & Toyoda, 1995). Auxiliary problems are simplified versions of the original problem. By presenting auxiliary problems, new scaffolds can be presented to learners who have failed to solve problems, it is expected that they will be able to find the correct solutions. The learning effect of presenting such auxiliary problems has already been confirmed in a problem exercise system that does not apply EBS (Hayashi, Shinohara, Yamamoto, Hayashi, Horiguchi & Hirashima, 2014).

We previously developed and evaluated an extension of the conventional EBS system. The extended EBS system can adaptively and automatically present auxiliary problems by diagnosing concepts that the learner does not understand, based on trends in incorrect learner responses (Aikawa, Koike & Tomoto, 2020a). We also improved and evaluated problem sequences in the system (Aikawa, Koike & Tomoto, 2020b).

In this study, we conducted additional experiments with our system (Aikawa et al., 2020b) and analyzed those learning activities. The resulting analysis of system logs indicated that learning activities with automated auxiliary problem presentation effectively resolved learner impasses in EBS.

2. Physics Error-based Simulation (Physics EBS)

A physics EBS system generates simulations of "assumed correct" phenomena based on learner answers (Hirashima et al., 1998), helping learners viewing the simulation to find errors. Learners can deepen their knowledge by noticing errors themselves, thereby obtaining learning effects.

A physics EBS system first presents a diagram of a certain phenomenon, and the learner is tasked with drawing arrows that indicate the forces acting on the objects in the diagram. Learner errors include drawing wrong forces or not drawing an existing force. From the learner input, the EBS system simulates strange behavior if the drawing is incorrect or natural behavior if the drawing is correct.

For example, Figure 2 shows examples of incorrect and correct user depictions of gravity and the normal force acting on a stationary object. If the learner enters only the gravity arrow as in Figure 2(a1), the EBS system presents a simulation in which the object falls through the floor at a constant acceleration because there is no force to counteract gravity, as in Figure 2(a2). Because this behavior is impossible in reality, the learner can see that their answer is wrong. The learner can then add an arrow to balance the gravity and the normal force, as in Figure 2(b1), thereby generating a simulation in which the object remains stationary on the floor. Such activities allow the learner to correctly understand the normal force, making an EBS system effective for learning physics (Hirashima, Imai, Horiguchi & Tomoto, 2009).

EBS systems simulate phenomena occurring when erroneous learner knowledge as demonstrated through answers is assumed correct, but these systems do not provide correct answers. Consequently, some learners reach an impasse.

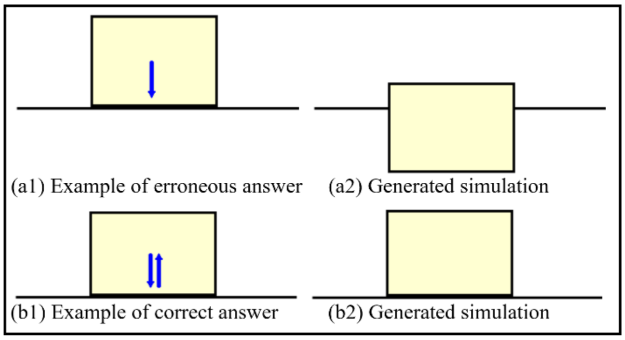
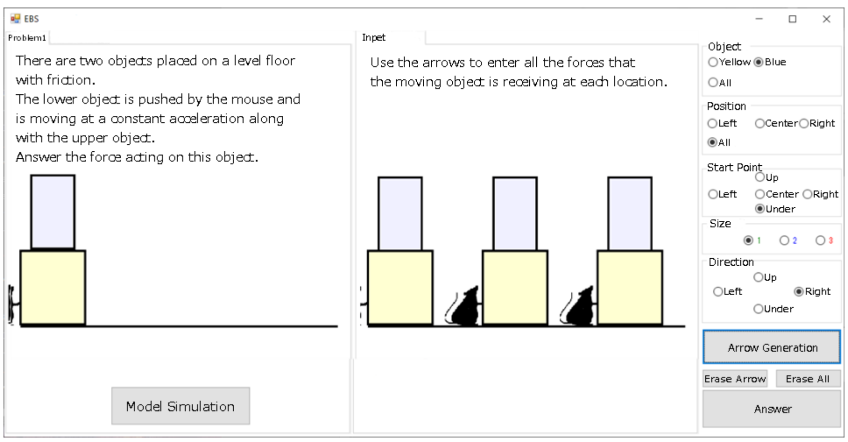
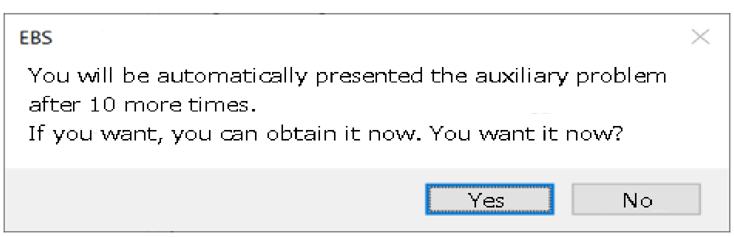


Figure 2. Example of EBS.

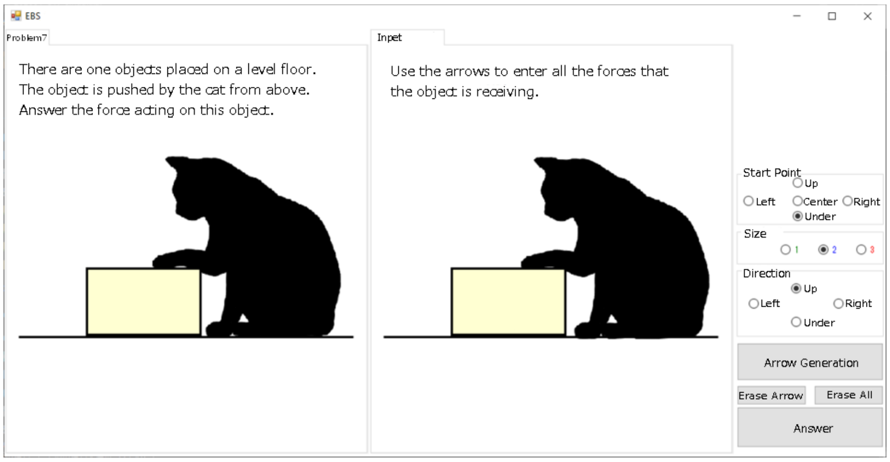
3. Physics EBS with Automated Auxiliary Problem Presentation



a) Problem presentation screen.



b) Auxiliary problem presentation message.



(c) Auxiliary problem presentation screen.
Figure 3. Example screens from the developed system.

We developed a system in which auxiliary problems are introduced into a conventional EBS to help learners resolve impasses in EBS problems. Simple auxiliary problem is presented to learners failing to provide a correct solution a predetermined number of times.

Our system uses answer histories to analyze causes of impasses, and then presents appropriate auxiliary problems. By correctly solving auxiliary problems, the learner gradually returns to the original problem. If the learner continues to make errors, the answer history is analyzed again, and the process shifts to another appropriate auxiliary problem. Learners can thus resolve impasses by themselves.

Figure 3 shows example screens in the developed system. The system first presents a problem like that shown in Figure 3(a). The learner answers the presented problem by drawing arrows on the input screen on the right side of Figure 3(a). If the learner makes an error five times, a message like that in Figure 3(b) appears, asking if the learner would like to attempt an auxiliary problem. If "Yes" is selected, the system presents an auxiliary problem like that shown in Figure 3(c). And if "No" is selected, the system presents the same problem repeatedly until 15 times. If it exceeds 15 times, the learner automatically shifts to the auxiliary problem.

Sequencing is important when presenting auxiliary problems. In particular, it is necessary to clarify differences between each problem and to adaptively sequence according to learner knowledge states. Therefore, we reconsidered problem sequencing based on the causal reasoning theory of force and motion by Mizoguchi et al. (2016) and implemented the results in a learning support system.

3.1 Design of Auxiliary Problems

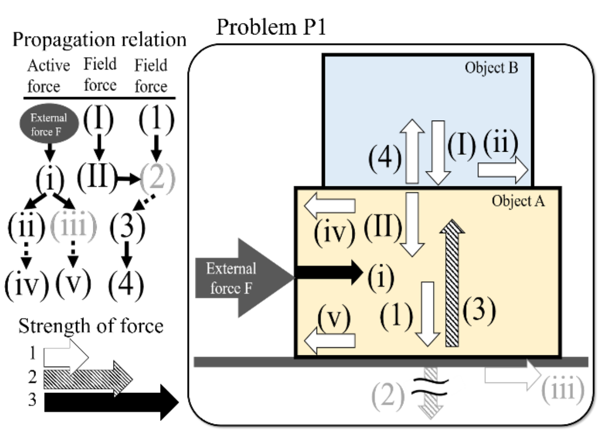


Figure 4. An original problem.

The auxiliary problem for this system was created by referring to the causal reasoning theory of force and motion by Mizoguchi et al. (2016). Elementary mechanics in school education focuses on understanding phenomena using equations. However, the causal relationship cannot be understood by equations. For example, in Figure 4, (I) is generated first, and then (II) is generated by (I), but the equation does not know the order of generation of such forces, and the interpretation is entrusted to the learner. Causal understanding is the understanding of the order of force generation. By creating auxiliary problems based on causal reasoning theory, learners can learn in the easy-to-understand order. However, we carefully considered there to be no contradiction between the equational understanding and the causal understanding.

Figure 4 shows a problem (P1) originally presented in the system. In this problem, objects A and B are placed on a floor, object A is pushed from the side, and both objects slide from left to right under constant acceleration.

If this problem is interpreted using causal inference, gravity acts on the objects A and B, as indicated by arrows (1) and (I). The gravitational force of object B acts on object A, as indicated by arrow (II), and each of those forces act on the floor as indicated by arrow (2). As arrow (3) indicates, the normal force from the floor pushes back on object A, which in turn pushes back on object B, as indicated by arrow (4). Objects A and B remain stationary because of the vertical directions of these arrows. Also, object A tries to move left to right due to the external force F represented by arrow (i), with that force propagating to object B and the floor, as shown by arrows (ii) and (iii). As a result, a frictional force acts at each contact surface, as shown by arrows (iv) and (v). This problem depicts constant acceleration with no initial velocity, so movement results from an external force exceeding the frictional force, and a constant sideways force results in acceleration. Arrow (ii) indicates the resultant force, so objects A and B move at the same acceleration. From this, we created the simplified auxiliary problems shown in Figure 5.

Problem P6 is a simplified problem in which the vertical force in Problem P1 is easily learned. Without external force F, no sideways propagation of force occurs. This auxiliary problem thus allows learners to consider only vertical forces.

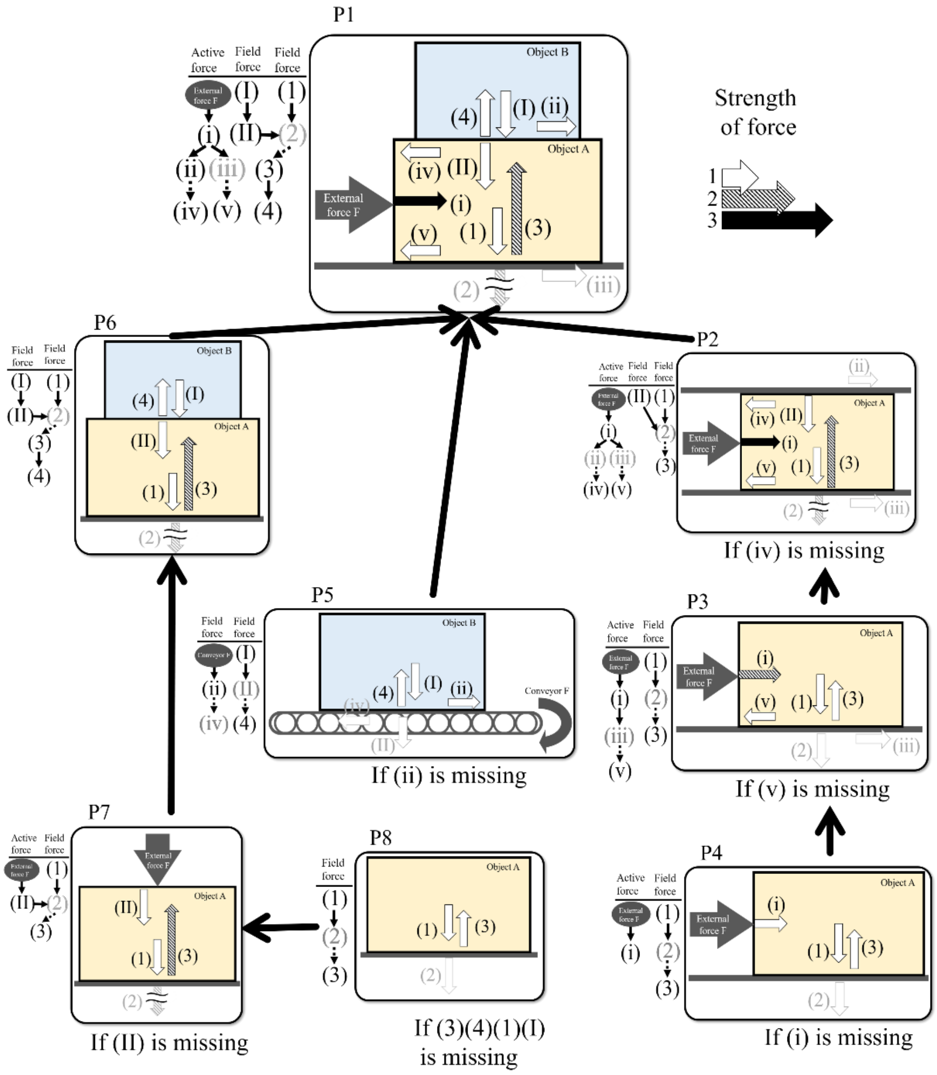


Figure 5. Problem sequences.

Problem P7 is simplified so that the force represented by arrow (II) in Problems P1 and P6 can be easily learned. In those problems, arrow (II) indicates propagation from gravity (arrow (I)) acting on object B. Therefore, to consider arrow (II), it is necessary to consider the propagation relation between (I) and (II). Therefore, by omitting the causal relationship between (I) and (II) and making the force (I) that causes (II) the external force F, the learner can easily recognize the force of (II).

Problem P2 is a simplified problem that makes it easier to learn the forces indicated by arrows (iv) and (v) in Problem P1 by omitting requirements for considering propagation of gravitational force from object B in the vertical direction.

Problem P3 removes the need to consider the relation between force (ii) and the frictional force (iv) generated by propagation from problem P2.

Problem P4 eliminates the frictional force from problem P3, removing the need to consider force (iii) and the resulting force (v).

Problem P5 removes the force on object A in problem P1, which generates force (ii) when the lower object A tries to move by force (i). In this problem, force (i) is directly generated by moving the floor with a belt conveyor.

Problem P8 is a simplified problem that eliminates forces received from above and lateral forces in all problems. This facilitates learning of gravity ((1) and (I)) and normal drag ((3) and (4)).

3.2 Problem Sequences and Presentation Method

Figure 5 shows the simplified problems described in section 3.1 as a sequencing diagram. This system first presents problem P1 and shifts to simpler problems according to the learner's errors. The system first compares the learner's answers with the correct answers to extract differing forces, which are considered to be misunderstood by the learner. Problem transitioning is based on these discovered differences. In this study, we first shift to the simplest problem, which involves the misunderstood force. As each problem is solved, the system gradually increases the difficulty based on edge relations.

For example, in problem P1, if the learner has not depicted the force (II) acting on the lower object from object B above, the system presents the simplest problem involving force (II), namely problem P7. In Problem P1, to guide force (II), it is necessary to understand that gravitational force (I) is generated in object B, and (II) is generated by the propagation of that force. Problem P7 is easier to understand because force (II) is directly generated by the external force. After problem P7 is solved, complexity increases in order of problem P6, then problem P1. If the frictional force (v) generated between the floor and object A is not described in Problem P1, the system presents Problem P3, which is the simplest problem involving force (v).

4. Evaluation

4.1 Method

We performed experiments to verify the learning effects from the automatically presented auxiliary problems in the developed EBS. Participants in each experiment were 13 engineering department university students who had studied elementary mechanics. Experiments comprised the following steps:

(1) Pre-test (7 minutes)
(2) System use (40 minutes)
(3) Post-test (7 minutes)
(4) Questionnaire

Before conducting the experiments, we sufficiently described the answering method and system operations. In step (2), we randomly assigned eight participants to an experimental group and five to a control group because they have each participated in other times and we could not compare the pre-test scores before their assignment. The experimental group used an EBS that automatically shifts to the auxiliary problem, whereas the control group used an EBS that allows learners to optionally select auxiliary problems. As mentioned in Chapter 3, the system asks if the learner would like to attempt an auxiliary problem if the learner makes an error five times. The learner has the option to shift up to 15 times, but after 15 times the shift is automatic. In EBS that automatically shifts to the auxiliary problem, the system automatically selects auxiliary problems that are adaptive to the cause of the learner's impasse. And in EBS that allows learners to optionally select auxiliary problems, a list of problems is displayed, and the learner selects an auxiliary problem from the list.

In steps (1) and (3), participants took a paper test in which they indicated forces acting on the presented phenomena as arrows. Both tests had seven problems.

4.2 Results

4.2.1 Tests and Questionnaires

Table 1. *Pre-test and Post-test Results*

	Pre-test		Post-test		Differences
	Avg.	S.D.	Avg.	S.D.	Avg.
Exp.	2.37	1.22	3.75	1.20	1.38
Ctrl.	2.40	0.49	3.40	0.49	1.00

All tests were scored as one point per correctly solved problem. Table 1 shows the means and standard deviations for pre- and post-tests.

Each mean score in Table 1 increased from the pre-test to the post-test. However, analysis of variance did not indicate a significant difference, suggesting no significant difference in learning effects.

Table 2 summarizes some of the results from the questionnaire, which used a six-level ranking from "very much" (6) to "very little" (1). We considered questionnaire item responses of 4 to 6 as positive, and responses of 1 to 3 as negative.

Table 2. *Questionnaire Results*

Question	Exp.		Ctrl.	
	Ps.	Ng.	Ps.	Ng.
(a) Do you think learning through this system will help you obtain correct answers?	7	1	5	0
(b) (Experimental group only) Do you think the simplified problems presented by the system were appropriate?	7	1	--	--
(c) (Control group only) Do you think the simplified problems you chose were appropriate?	--	--	4	1
(d) Do you think the simplified problems presented by the system advanced your learning?	7	1	4	1
(e) Do you think the simplified problems presented by the system led you to correct solutions of the original problem?	7	1	5	0

All five participants in the control group, which used a system allowing free selection of simplified problems, positively responded to question (a). Seven of eight participants in the experimental group, which responded to auxiliary problems presented by the system, responded positively whereas only one answered negatively. The participant who answered negatively are not the same person.

This experiment indicated learning effects for both the system used by the experimental group and that used by the control group, with positive results being obtained from nearly all questionnaire items. However, there was no significant difference between the control group and the experimental group in 2 (the group of experimental or control) x 2 (the timing of pre- and post-test) ANOVA. The questionnaire also suggested that the control group thought they could appropriately select simplified problems by themselves.

In this study, we considered that learners solving complex problems would have difficulty understanding what points were misunderstood and which auxiliary problems should be solved. However, we found that participants with sufficient ability grasped their own misunderstandings, and that when given a list of appropriately designed auxiliary problems, they could self-select appropriate problems. Furthermore, self-selection of problems may provide more information than the system does. The experimental group can see only limited auxiliary problems unless they make various mistakes. If there is only one pattern of mistakes, learners may see only one auxiliary problem. On the other hand, the control group can arbitrarily see all the auxiliary problems. The control group acquires a lot of information because many auxiliary problems can be seen. For example, in question (c), four out of five participants in the control group stated that they were able to select an appropriate question. This is likely one reason why testing indicated no significant difference. We, therefore, found that effective learning is possible for participants with high self-learning ability when they are presented with an appropriate collection of auxiliary problems and the EBS functions without automated auxiliary problem presentations like the control group. In the future, it will be necessary to consider whether the participants in these experiments were appropriate as target users. In addition, the experimental group and the control group were randomly assigned, but the experiments will be conducted by assigning them evenly based on the scores of the pre-test from next time.

4.2.2 Analysis of Learning Activities

Table 3 shows the problem sequences and analysis results for problem transitions by 13 learners, designated as A through M. The "Detected cause of impasse" column shows the cause as determined by the system when the learner first attempted problem P1. In this system, the learner shifts to the auxiliary problem corresponding to the cause of the impasse after attempting the problem a certain number of times. "Number of problems shifts until solved cause of impasse" shows the number of shifts until arriving at a problem that suggests resolution of the cause of a detected impasse, and " (Total number)" is the total number of times the learner moved to the problem. "Exercise completed" shows whether the learner was able to correctly answer problem P1 within 40 min.

Table 3. *Analysis of Problem Transitions by Learner*

Participants	Detected cause of impasse	Number of problems shifts until solved cause of impasse (Total number)	Problem shifts by learner (* resolved cause of impasse)	Exercise completed
Experimental group				
A	(ii)	1 (2)	P1 → P5* → P1	Yes
B	(iv)	1 (2)	P1 → P2* → P1	Yes
C	(v)	1 (8)	P1 → P3* → P2 → P1 → …	No
D	(II)	– (8)	P1 → P7 → P6 → P7 → P6 → …	No
E	(II)	2 (6)	P1 → P7 → P6* → P1 → …	Yes
F	(v)	1 (7)	P1 → P3* → P2 → P1 → …	Yes
G	(ii)	– (3)	P1 → P5 → | P1 → P2 → |	No
H	(v)	4 (6)	P1 → P3 → | P1 → P2 → P3* → …	Yes
Control group				
I	(II)	10 (14)	P1 → P8 → P6 → P7 → P3 → …	Yes
J	(ii)	8 (12)	P1 → P6 → P7 → P3 → P4 → …	Yes
K	(v)	10 (13)	P1 → P8 → P4 → P3 → P7 → …	Yes
L	(iv)	1 (2)	P1 → P2* → P1	Yes
M	(iv)	– (15)	P1 → P8 → P6 → P7 → P3 → …	No

| indicates a system restart; → indicates problem transition after an incorrect answer; → indicates problem transition after a correct answer

The average value in the "Number of problems shifts until solved cause of impasse" column is 1.67 for the experimental group and 7.25 for the control group. The average total number of transitions was 5.25 for the experimental group and 11.2 for the control group. In both cases, the experimental group showed lower values compared with the control group, suggesting that this system appropriately shifted to auxiliary problems corresponding to the causes of learner impasses. However, in the "Exercise completed", one out of five participants in the control group failed, while three out of eight participants in the experimental group failed. Therefore, we considered that "Exercise completed" is possibly influenced by the learner's ability to voluntarily select auxiliary problems in the control group. However, at present, the number of experiment participants is not sufficient, so it is necessary to further investigate the relationship between "Exercise completed" and "Number of problems shifts until solved cause of impasse" after increasing the number of participants. Detailed learning activities are individually investigated from the problem transition history for each participant.

We first describe participants in the experimental group shown in Table 3. Participant-A got stuck on problem P1 due to frictional forces (ii) and (iv), and so moved to an auxiliary problem corresponding to frictional force (ii). Correctly answering problem P5, Participant-A returned to problem P1 and correctly answered it. This suggests that shifting to problem P5 allowed Participant-A to resolve the frictional force (ii) impasse.

Participant-B got stuck on frictional force (iv) in problem P1, and so shifted to problem P2 involving frictional force (iv). After correctly answering problem P2, Participant-B returned to problem P1 and correctly answered it. This suggests that shifting to problem P2 allowed Participant-B to resolve the frictional force (iv) impasse.

Participant-C got stuck on the frictional forces (ii), (iv), and (v) in problem P1. Following the system priority, C first moved to problem P3, which addresses frictional force (v). After correctly answering problem P3, C then moved to problem P2 in accordance with the problem sequencing, and correctly answered that problem. After returning to problem P1 and working on it, C did not arrive at the correct answer, but there was no frictional force (v) among the system-diagnosed causes at that time. This suggests that Participant-C could not correctly answer problem P1, but did resolve the frictional force (v) impasse.

Participant-D is excluded from the analysis in this paper. Participant-D got stuck due to force (II), where the upper object in problem P1 pushed against the lower object. D then shifted to problem P7. However, when problem P7 was correctly answered and problem P6 was attempted, Participant-D got stuck on force (II), in which the upper object pushes on the lower object. Participant-D again returned to problem P7 in the same manner, then moved to problem P6 and provided an incorrect answer. This was repeated many times, seemingly because the auxiliary problem was ineffective and thus inappropriate for problem sequence evaluation.

We next describe the control group participants, where the system does not adaptively present auxiliary problems, allowing learners to self-select auxiliary problems.

After solving problem P1, Participant-I chose problem P8 and then problem P6. In this way, Participant-I tried all the auxiliary problems in order. When the cause of the impasse was determined in the same manner as in the experimental group, Participant-I got stuck on the force of the upper object pushing on the lower object and the frictional forces (ii) and (iv) in the first problem P1. Participant-I attempted problem P7, addressing the force of the upper object pushing on the lower object, and problem P2 for the frictional force (iv). After that, Participant-I answered problem P1, with no error extracted. The auxiliary problem therefore seems to be effective. However, the transition was repeated three times before moving to problem P7 and nine times before moving to problem P2. Participant-I also attempted problem P7 twice. Despite submitted a correct answer on the first attempt, when reattempting problem P1, Participant-I again made a mistake regarding the force of the upper object pushing on the lower object. This is likely because Participant-I did not attempt the problem in sequence, and so could not successfully combine knowledge from problem P7 with that from problem P1. Similar behavior was observed for other control group participants.

Participant-L performed only two problem transitions, selecting the auxiliary problem corresponding to the cause of the impasse on the first attempt and resolving it. This suggests that Participant-L was able to select the appropriate problem by being aware of sources of misunderstanding.

The above results suggest that problem transitions resolve the cause of the impasse as analyzed by the system. This should decrease learning load because there were fewer transitions until elimination of the cause of the impasse in the experimental group than in the control group. Problem sequencing and auxiliary problem presentation in this system thus effectively eliminated impasses. Note that Participant-D was excluded from the analysis in this paper, but is nonetheless an important case. In particular, Participant-D could not resolve the impasse even with problem transitions because the auxiliary problems did not provide appropriate clues. This case requires further investigation in the future.

In addition, the average and standard deviation were calculated in the experimental group and the control group of the total number of answers. The average was 34.25 in the experimental group and 37 in the control group, and the standard deviation was 10.06 in the experimental group and 18.13 in the control group. Since there is almost no difference in the average, it is considered that there is no large difference in the amount of trial and error between the experimental group and the control group.

And since the standard deviation is larger in the control group, it can be seen that the amount of trial and error in the control group varied greatly among individuals compared to the experimental group. This suggests that this system does not suppress the amount of trial and error. Originally, EBS emphasized the promotion of trial and error. but, in this study, we are conducting an activity different from EBS, which is to support learners by issuing auxiliary problems in order to solve the impasse. We would like to improve and investigate the system so that it will have a positive effect on the original trial and error of EBS.

5. Conclusion

We developed a system that introduces an adaptive auxiliary problem presentation function to conventional EBS as a method of supporting problem-solving in EBS. We also evaluated the effectiveness of auxiliary problem presentation through evaluation experiments, using system logs to determine whether the system supports the resolution of impasses. As a result, we found that the cause of the learner's impasse as analyzed by the system was resolved by the corresponding auxiliary problems presented by the system. This suggests that the problem series constructed in this study are useful in resolving impasses.

In future work, we will investigate problem presentation methods that consider learning histories when selecting auxiliary problems. We will then apply such methods to the present system and perform evaluation experiments. We will also examine cases in which auxiliary problems were ineffective and consider more effective alternatives. In addition, we investigate not only the number of problems shifted until solved cause of the impasse but also the problem-solving time for the experiments in this paper.

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