Simulation-Based Scientific Discovery Learning: A Research on the effects of Experimental Support and Learners' Reasoning Ability

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Abstract

On the basis of our previous research, the present study made a further investigation on how to support simulation-based scientific discovery learning form the scientific experiment and reasoning perspective. A 2 (ES / no ES) × 3 (high / middle / low) between-subjects design was adopted to examine the effect of the experimental support (ES) and learners' reasoning ability. In result, (1) clear main effects were observed for reasoning ability level on the posttest of principle knowledge and intuitive understanding, (2) there was an interaction between the ES and reasoning ability level on the posttest of principle knowledge, indicating that ES had positive influence to low ability learners, however had negative influence to middle ability learners. A process analysis manifested that the learners with the ES had performed more qualified and well-controlled experiments. Conclusion was drawn concerning how to support scientific discovery learning in simulation environment.

Keywords

simulation-based learning, scientific discovery learning, learning support, learning environment design

Introduction

A growing number of studies have focused on scientific discovery learning through computer simulation within a constructivist paradigm. However, many researches designed to compare the effects of simulation-based learning to more traditional modes of learning find little persuasive evidence in its favour [1][2]. The question arises, why does simulation-based learning, involving learners in active inquiry, not improve learning outcomes more consistently? One explanation lies in the wide range of difficulties learners may encounter in coping with discovery learning processes. De Jong and van Joolingen [3] classified the problems that learners may encounter into four categories: (a) difficulties in handling hypotheses, (b) poorly designed experiments, (c) difficulties in data interpretation, and (d) problems regarding the regulation of discovery learning. Despite its potential in stimulating constructive learning activities, it seems that the simulation-based learning environment cannot guarantee effective learning without sufficient support ("scaffolding") for discovery learning activities. This conclusion has also been supported by Lee's [4] meta analysis showing that hybrid simulation involving instructional elements is more effective than pure simulation for new content learning. Some studies have been conducted to help learners with particular strategies from specific aspects. For example, some researchers developed supportive methods to help generate hypothesis in simulation-based discovery learning [5] [6] [7]. Others have looked at the issues connected with experimental design [8], planning [9], explaining the phenomenon and predicting the result [10], and access to an appropriate knowledge base [11].

In most studies, scientific discovery learning is regarded as a scientific reasoning process that involves the generation of hypotheses and testing them against the collected evidence [12]. However, scientific discovery learning is not merely a logical reasoning process. Looked at from a constructivist perspective, scientific discovery learning also involves the activation of prior knowledge, the interpretation of problem situations, the explanation of experimental outcomes, and the modification and integration of conceptual understanding. Scientific discovery learning also means a generative process of meaning-making, which constitutes another perspective in the learning activity. On this sense, the following inner conditions will influence scientific discovery learning therefor. First, as a scientific reasoning process, discovery learning depends heavily on learners' logical and systematic experimental and reasoning activities. Second, as a process of generative meaning-making, its effect will be decided by learners' interpretative and explanatory activities. Also, learners need to keep reflecting on their discovery process to lead to the integrative understanding of discoveries.

In an earlier study on supporting discovery learning in secondary physics domain (upthrusts on floating objects), we [13] investigated the effects of two types of learning support embedded in simulation environment: (a) experimental support that scaffolded learners in the systematic design of experiments, the prediction and observation of outcomes, and the drawing of conclusions, and (b) interpretative support that helped learners with knowledge access and the generation of integrative understanding. In results, The interpretative support manifested prominent main effects on the posttests of intuitive understanding, flexible application and knowledge integration. However, there was no significant effect for the experimental support on the posttests or the indices designed to evaluate learners' experiment designs. A clear interaction between experimental support and learners' science ability was observed on an index evaluating learners' experimental designs, which implied that learners with higher science achievement could benefit more from the experimental support. The experimental support in this study included a number of elements such as the explanation about experiment design (especially "varying one thing at a time"), the prompts about identifying the objective of each experiment, predicting and observing outcomes, and summarizing their discoveries. However, these treatments were still not supportive enough to improve learners' experimental activities or the learning outcomes. This result disagrees with Rivers and Vockell's [14] finding that providing learners with general experimentation hints before their exploration could promote their experimentation abilities, as well as Swaak et al.'s [15] conclusion that the experimental support in form of assignments had clear effect on scientific discovery learning.

The present study will continue to explore how to support learners' scientific discovery learning from the experiment and reasoning perspective. In the study mentioned above, we merely gave learners a general explanation about experiment design (e.g. "You'd better vary one factor at a time, otherwise you cannot make clear which factor is having an effect."). The present study will improve the support by giving a specific example of experiment design before the formal experiment. In addition, some treatments of the ES in form of questions will be changed from selective ones to compulsive ones. Besides, in order to investigate the interaction between learners' reasoning ability and experimental activities, this study will include the reasoning ability level as a between-subjects factor. Rather than using science achievement as the grouping variable, the present study will use the Raven's Progressive Matrices to identify learners' reasoning ability.

Method

The simulation-based learning environment

The domain chosen for the simulation was floating and sinking, where the subjects were required to explore the upthrust on objects submerged in water (see Fig.1). Their task was to discover which one or more of three given factors (shape, mass and volume) were related to the size of the upthrust on an object. Learners often hold misconceptions about this phenomenon, assuming that the size of the upthrust depends on the shape or mass of the object. Actually, the upthrust equals the weight of the water excluded by the object. The size of the upthrust depends only on the volume of the object.

The simulation adopted paired-instance design that requires learners to construct a pair of experiments at a time, so that they could contrast the outcomes of two instances directly. For example, in order to examine the effect of the mass of object, a learner can select two objects of the same shape (e.g. ball) for the left and right side, keep the volumes the same and vary their masses to be different. Then he/she can click the "RUN" button to see whether the upthrusts will be different or not in result. For all the subjects, a data sheet was provided on screen to record and display the value of the input and the output variable in each pair of experiments. In addition, a permanent button "Main Steps" was prepared to remind learners of the main steps in an experiment.

Fig.1: Interface of the simulation

For the learners in experimental group, the learning environment contained some experimental supports (ES) to help learners designing valid experiments. The ES included four specific treatments. (a) At the beginning, the program gave learners some general explanations about scientific experimental design (particularly "varying one thing at a time") and exemplified the idea, with the case of dissolution (which factors are related to the speed of dissolution). (b) Before designing each pair of experiments, learners were required to identify their objective by ticking the variable(s) (shape, mass and volume) they wanted to examine. (c) Learners were required to predict which of the two specified objects would have the larger upthrust before running the experiments, and to check their predictions after the experiments. (d) After each pair of experiments, they were asked to conclude their discovery against a table showing which variables were the same or different between the two objects (see Appendix I).

The simulation program was written in such a way that it registered learners' manipulations during the learning processes and wrote a log-file for each subject.

Design

In order to investigate the effects of the ES among learners with different reasoning ability, a 2 (ES / no ES) $\times$ 3 (high/ middle / low) between-subjects design was used to compare two versions of basically the same simulation environment: ES and no ES. Log-files were used to analyze how learners processed their discovery learning and utilized the ES.

Subjects

Subjects were 80 students of the eighth grade from a junior high school in the urban of Beijing. The students were 13 year old in average. Thirty of the students were girls and fifty were boys. They were grouped into three levels (high / middle / low) according to their scores on the Raven's Standard Progressive Matrices test. The students of each level were then randomly assigned to two conditions: ES or no ES.

Posttests

Three aspects of the outcome of discovery learning were assessed in the posttests.

Principle knowledge. This was assessed by seven multiple-choice items. One item focused on the general principle about factors that can affect the upthrust on the object submerged in water. The others concerned with specific principles underpinning the phenomenon.

Intuitive understanding. Five multiple-choice items measured learners' intuitive understanding, which is regarded as an important goal in scientific discovery learning [10]. Using pictures, these items showed pairs of objects with different combinations of shapes, masses, and volumes and asked learners to predict how their upthrusts would compare in size.

Flexible Application. Eight items were written to determine how well learners could generalize and apply the knowledge to new situations. These questions were more flexible, requiring the transformation and integration of learners' knowledge.

Procedure

All the students were given the Raven's Standard Progressive Matrices test two weeks before the experiment. The experiment took place in a computer laboratory equipped with 50 networked Pentium computers. The subjects were required to finish the following sessions individually:

Warm-up. Subjects worked with a tutorial version of the simulation program. Three experimenters were present to answer questions regarding the program. This stage lasted approximately 10 minutes.

Problem presentation. The subjects were asked to explore which one or more of the factors among shape, mass and volume could influence the upthrust on an object submerged in water. A brief description of the problem was available on the top-right corner of the screen throughout the discovery process.

Exploration. Subjects were reminded that their task was to discover the rule on the basis of sufficient evidence through simulated experiments.

Posttest. The posttests in written format were administered immediately after the completion of the exploration. A total of 30 minutes was allotted for this session.

Results

Two main sets of results are presented: 1. The effect of the ES on the posttests among students of different reasoning ability levels. 2. A process analysis to investigate how the subjects had used the supports and designed their experiments.

The effects of the ES and reasoning ability on the posttest

Table 1 shows the mean scores and the standard deviations of the different groups on the three categories of the posttests. The full score of each category is 1.00.

	Principle	Intuitive	Flexible

		knowledge		understanding		Application	
		M	SD	M	SD	M	SD
High ability	ES	.88	.21	.83	.24	.43	.19
	no ES	.90	.26	.93	.20	.46	.15
Middle ability	ES	.60	.43	.77	.27	.42	.13
	No ES	.88	.31	.85	.28	.39	.15
Low ability	ES	.68	.41	.71	.31	.38	.17
	no ES	.41	.42	.71	.25	.40	.18
Total		.73	.38	.81	.26	.42	.16

Table 1: The means and standard deviations of three types of posttests

Principle knowledge. In the ANOVA using ES and reasoning ability level as between-subjects factors, a significant main effect was observed for the reasoning ability on the principle knowledge test (F (2, 74) = 7.06, p < .01). Those with higher reasoning ability could accomplish the discovery task more successfully. There was no significant main effect for ES. However, there was a significant interaction between ES and reasoning ability (F (2, 74) = 3.85, p < .05) (see Fig.2). Simple effect analysis revealed that ES had significant positive effect among low ability subjects (F (1, 76) = 4.00, p < .05), but had marginally significant negative effect among middle ability subjects (1, 76) = 2.81, p < .10). ES had no significant influence to subjects with high reasoning ability (p > .10).

Intuitive understanding. There was a marginally significant main effect with reasoning ability (F (2, 74) = 3.00, p = .06). The subjects with higher reasoning ability scored higher on this test. No significant effect had been found for ES or its interaction with reasoning ability (p > .10).

Flexible application. There was no significant effect for ES or reasoning ability level on the flexible application test (p > .10).

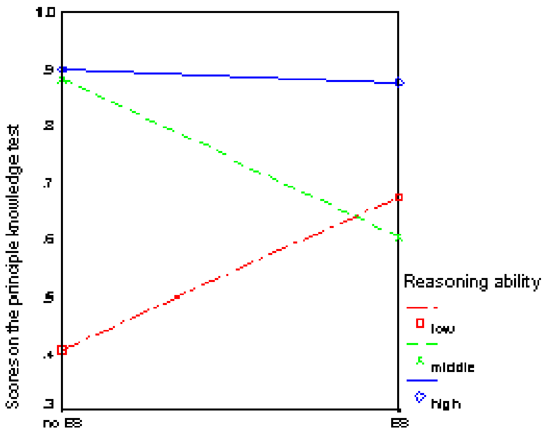

Fig. 2: Interaction of ES and reasoning ability on the principle knowledge test

Process analysis

Using the data provided by the log-files, an analysis was made to see how the subjects had interacted with the simulation environment and how they had used the provided supports.

Number of experiments and time on exploration. A maximum time of 35 minutes and a minimum number of seven pairs of experiments had been set for the exploration session. Subjects conducted 8.57 (SD = 2.26) pairs of valid experiments on average. The learners who received the ES performed significantly fewer experiments than those without the ES, $F(1, 68) = 4.33$, $p < .05$. There was no significant difference concerning reasoning ability level ($p > .10$).

Evaluation of learners' experiments. "Change one thing at a time" is an important principle in scientific experiment. Unfortunately, learners are often found to vary many variables in one experiment [16][3]. Surrounding this principle, three indices were constructed to evaluate the experiments designed by subjects. (a) Index I: The ratio of well-controlled experiments: it indicated the percent of the paired experiments in which one and only one factor was varied among shape, mass, and volume. (b) Index II: Average number of variables varied in each pair of experiments: this is a looser criterion that counted how many variables among shape, mass and volume were varied in each pair of experiments. (c) Index III: Focused examination of the three variables: we identified a pair of experiments as having undergone a “focused examination” of certain variable (shape, mass or volume) if that variable was the only variable that was varied in that pair of experiments. For each variable, a full score of 2 was given when it had been examined by at least two pairs of experiments at different levels of the controlled variables (an example is shown in Appendix II). Score 1 indicated that the variable had been examined by only one pair of experiments or by more than one pair of experiments but at constant levels of controlled variables. Sequentially, score 0 meant that no experiment had been focused on this variable at all. An average score across the three variables was used in the final analysis. Learners' scores on the three indices are shown in Table 2.

Groups		Index I		Index II		Index III	
		M(%)	SD	M	SD	M	SD
High ability	ES	48.90	.15	1.58	.22	1.08	.38
	no ES	49.82	.19	1.67	.32	1.20	.44
Middle ability	ES	52.39	.18	1.60	.24	.82	.40
	No ES	43.95	.23	1.72	.35	.97	.43
Low ability	ES	58.42	.25	1.52	.42	.82	.43
	no ES	36.24	.21	2.00	.47	.81	.41
Total		48.26	.21	1.69	.37	.97	.44

Table 2: The means and standard deviations of the indices evaluating learners' experiments

Note: Index I: The ratio of well-controlled experiments in which only one variable was varied;

Index II: Average number of variables changed in each pair of experiments (maximum=3);

Index III: Focused examination of the three variables (the full score is 2).

ANOVAs of the three indices using ES and reasoning ability level as independent variables displayed that ES had significant positive effects on Index I ($F(1, 68) = 4.31$, $p < .05$) and Index II ($F(1, 68) = 7.98$, $p < .01$). A significant effect was found for the reasoning ability on Index III ($F(2, 68) = 4.29$, $p < .05$).

Correlation between the quality of experiments and the posttests. In order to explore the relationship between the quality of experiments and the result of discovery learning, we calculated the Pearson Correlation between each of the indices and the aspects of posttests (see Table 3). Significant correlation was observed between the three indices and the principle knowledge and intuitive understanding tests.

Tests	Index I	Index II	Index III
PK	.328**	-.418**	.439**
IU	.255*	-.259*	.372**
FA	.047	-.066	.116

Table 3: Correlation between the quality of experiments and the posttests

Note: PK: Principle Knowledge; IU: Intuitive Understanding; FA: Flexible application

* p<.05, ** p<.01

Discussion

This study made a further investigation on how to support learners' scientific discovery learning from the experiment and reasoning perspective. The ES included such treatments as explaining and exemplifying the principles and strategies in designing scientific experiment, questions prompting learners to decide the factor(s) to be examined each time, to predict and check the outcomes, and to draw conclusions from the experiments.

The effect of ES was verified to a greater extent in this study than in our previous research [13]. As the process analysis tells us, the ES had significant main effects on two of the three indices evaluating learners' experiment designs. Students with the ES outperformed those without the ES in designing effective and well-controlled experiments. As we predicted, the improvement of the ES in this study did make some difference in comparison to its effect in the previous study. For the learners around 13 years old, it is not enough to tell them the general way to design an effective experiment. Detailed explanations and examples are necessary for them to understand the principles and strategies underpinning scientific experiment design.

The process analysis also demonstrated that there was significant correlation between each of the three indices and the posttests of principle knowledge and intuitive understanding. This result converged with our previous research displaying that learners who had discovered the right rule surpassed the failure subjects on all the three indices of experimental design [13]. We also found that learners' reasoning ability had a significant effect on the index III. Learners with higher reasoning ability had done more focused examinations of the three factors - shape, mass and volume of the object. All the outcomes support the importance of qualified reasoning and experimental activities in scientific discovery learning. As is emphasized by most researchers in this field, the perspective of scientific reasoning and experimental activities does account a lot in scientific discovery learning process. The result of discovery learning depends heavily on learners' such reasoning and experiment activities as systematic and focused manipulation of input variables, prediction and observation of outcomes, and drawing conclusions from experiments, etc. The inefficiencies in the above activities can hamper learners' successful discovery.

When it comes to the effect of the ES and reasoning ability level on the posttests, the reasoning ability had notable effect on the principle knowledge and intuitive understanding test. Learners with higher reasoning ability could discover the underlying rules in the phenomenon more successfully and formulate their insightful understanding about the relevant instances on the basis of the discovered rules. The effect of the reasoning ability was not observed on the flexible application test. One of the possible reasons might be that the items in this category were too difficult to differentiate the subjects.

The effect of the ES on the posttests was reflected to be quite complex in its interaction with reasoning ability level on the principle knowledge test. Whether the ES was present or not, the students having high reasoning ability could accomplish the discovery learning task quite well. They could construct proper strategies (e.g. controlling of extraneous variables in experiments) for their experiments relying on their own reasoning ability. The ES was the most helpful for the students with low reasoning ability. This trend is inconsistent with our previous research revealing that students with higher science achievement could benefit from the ES to greater extent. This inconsistency might be caused by the improvement of the ES in the present study, which included detailed explanation and example about experiment design, becoming much easier to be grasped by the low ability learners. The trickiest trend is the negative effect of the ES among the middle ability learners. Surprisingly, students without the ES exceeded those receiving the ES among the learners of middle reasoning abilities. A possible reason is that the ES has distracted learners from their thinking activities. Some of the treatments in the ES took the form of questions requiring learners to answer, for instance, ticking the factors to be examined, ticking one's predictions, checking the predictions, and drawing conclusions. All the tasks might cause extra cognitive load for learners and interrupt their thinking process. For the learners with low reasoning ability, the discovery task was just in their region of approximate development. They couldn't come up with the needed experiment strategies using their own reasoning ability. But they could do it resorting to the provided support. Therefore the ES was more the positive treatment than the negative one for these learners. The learners with high reasoning ability could avoid the negative influence of the ES because they had fairly stable ability to deal with the discovery task. Whilst for the middle ability learners, they had the very elementary (still unstable) ability to generate the needed experiment strategies. The negative influence of the extra cognitive load caused by the ES could be more prominent among the learners of this level. If this is the case, learning support in simulation environment must be adapted to the levels of the learners to maximize the benefit of the support and avoid the possible negative influence caused by the extra cognitive load. Further research need to be conducted to explore the possible cognitive load caused by the experimental support and to examine the effect of adaptive experimental support in simulation-based discovery learning.

Conclusion and Implication

This study implies that qualified experimental and reasoning activities play an essential role in simulation-based scientific discovery learning process. Experimental support embedded in simulation environment can function as the scaffolding for learners' discovery activities. Instructional designers need to take learners' reasoning ability into account to provide the experimental support that is exactly in the region of approximate development. However, experimental support might also cause extra cognitive load for learners, resulting in some negative influence to their discovery learning.

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Biography

Jianwei Zhang is now a Ph.D. candidate at Beijing Normal University, and will be a lecture in the Educational Technology Center at Tsinghua University after the July. His Ph.D. thesis focuses on simulation-based discovery learning and will continue to work with constructive learning in ICT environment, esp. Distance Learning.

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Appendix I The table showing which variable(s) were the same or different in the two chosen objects: An example.

	Shape	Mass	Volume	Upthrust

Same	✔		✔	✔
Different		✔		

Appendix II Focused examination of volume: An example that was given full score

No.	Shape	Mass (g)	Volume (cm^3)	Upthrust (N)
1 left	Ball	50.00	30.00	0.30
1 right	Ball	50.00	20.00	0.20
…				
3 left	Box	100.00	10.00	0.10
3 right	Box	100.00	40.00	0.40

In the case, both of the two pairs of experiments focused on the volume, which is the only independent variable that was different between the left and right object. Also these two pairs of experiments examined the effect of volume at different levels of the mass (50.00 and 100.00g) and shape (ball and box).

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