How Do Children Learn and Teach?
In-Class Collaborative Teaching Simulation on the Complex Doubly Structural Network

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Abstract: In this research, a novel teaching simulation model is proposed, in which the understanding status, knowledge structure, and collaborative effect of each learner are integrated through the concept of a doubly structural network model. The purpose of this research is to investigate how the learners’ understanding will be changed by various teaching styles in a classroom. The proposed model consists of students’ mental models, their learning capabilities, in-class learning processes, learning material structures, and their collaborative relationships. In the simulation experiments, we analyse the learning effects of both the different teaching strategies and the seating arrangement of learners on collaborative learning effects. From the simulation analyses, we have found that: (1) the learning effects depend on the difference in teaching strategies, (2) a teaching strategy where learning skills, material structure, and collaborative learning are integrated is the most effective, (3) the seating arrangement affects collaborative learning, and (4) ability classes have adverse effects on learners in collaborative learning.

Key Words: education, collaborative learning, complex network, learning system, simulation.

1. Introduction

In education, it is important to understand the status of the understanding of each learner and design instruction content according to his/her understanding status. Digitalization of learning environment, called e-learning, has enabled the accumulation of records containing a vast amount of information concerning the learning history of students. Many technologies to gain an understanding status of each learner sequentially have been produced [1],[2]. Additionally, there exist relationships between knowledge and the content to be instructed, and it is important to consider the structural dependency relationship when teaching is done. The effectiveness of the collaborative effect among learners has also been clarified [3].

When it comes to grasping an understanding level of each learner, conventional studies have only approached each level of learners so far. An approach to a classroom with a group of learners remains a matter of development. Metric methods for collaborative effects among learners also have room for development. In order to understand the actual conditions of teaching effects in a confined space such as a classroom, the understanding status, knowledge structure, and collaborative effect of each learner needs to be integrated for consideration. There is also room for development in approaches to this integration.

In the research field of network models, recently, a new model building method, referred to as complex doubly-structural network model (CDNM), has been proposed. This method utilises two different network models, the internal network model and the social network model. Through this research, we designed a new teaching simulation method built by using CDNM consisting of an internal network model, which considers the status of understanding, knowledge structure of the learner, and the social network, which considers the learning space. With this method, we considered a system that supports teaching activities of teachers.

By using CDNM in this research, we tried to integrate the understanding status, knowledge structure, and collaborative effect of each learner in order to simulate the actual conditions of the learners’ understanding for instructions given in a classroom. Moreover, we set and examined the issues described below by applying the simulation method.

1. What kind of influence could teaching strategies have on learning effects? (Experiment 1)
2. What kind of influence could collaborative teaching strategies have on learning effects? (Experiment 2)
3. What kind of influence could seating arrangements of learners have on learning effects? (Experiment 3)
4. What kind of influence could ability classes have on learning effects? (Experiment 4)

2. Related Work

The purpose of this research is to simulate the actual conditions of learners’ understanding of instructions given in a classroom, while we attempted to quantify interactions among teachers and learners in the classroom. In this research, we had the concept that individual learners have network relationships, where knowledge nodes are linked according to relevancy, and each of the learners understands what they learn while influenced by the relevancy of their own knowledge networks every time they learn in a classroom. Based on this concept, we tried to quantify the understanding levels.
In order to build a specific simulation model, we referred to the findings of the following three research fields: the test theory study, the study of probabilistic reasoning methods, and the study of network models [4],[5]. We acquired an understanding status of each learner by employing the findings of the test theory study, and understood the knowledge structure by utilising the findings of the study of probabilistic methods. We also incorporated the findings of the study of network models for building a simulation model for a classroom that contains collaborative effects with the understanding status and knowledge structure we gained. Based on these areas, we designed a method for simulating the actual conditions of understanding of instruction given in a classroom.

2.1 Test Theory Study

The status of understanding of learners, or academic evaluation, has been studied in a form of test theory [6]. In test theory, evaluation methods that use item response theory (IRT) have been proposed, which are moving closer to actual practical use. Based on a response to an item, IRT expresses the learner’s ability, the difficulty level of each item, and discrimination as functions. According to the number of parameters, there are calculation models such as the one-parameter logistic (1PL) model, two-parameter logistic (2PL) model, and three-parameter logistic (3PL) model.

The 2PL model can be expressed as formula 1. Each term in formula 1 indicates the following points: \( \theta \) = ability, \( a_j \) = discrimination, \( b_j \) = difficulty, \( P_j \) = probability of a correct response to an item \( j \):

\[
P_j(\theta,a_j,b_j) = \frac{1}{1 + \exp(-a_j(\theta - b_j))}. \tag{1}
\]

Discrimination and difficulty are referred to as the item parameter, while the learner’s ability is referred to as the ability parameter. Methods for estimating the item parameter and the ability parameter have been studied in [6]–[9].

2.2 Study of Probabilistic Reasoning Methods

Meanwhile, methods for quantifying the dependency relationships between events have been studied as probabilistic reasoning, where a logical framework called Bayesian approach was designed [10]–[13]. The Bayesian network applies to this theoretical framework, and this network is a calculation model that handles uncertain events. The Bayesian network handles each event as a probability variable. In addition, this network expresses the dependency relationship between multiple events in a graph form with nodes as each event and arrows that indicate the dependency relationship as a link.

As a study where the Bayesian-approached framework is applied, there is graphical test theory [14],[15]. This theory expresses a learning material structure graph by considering learning items as nodes and the dependency relationship between learning items as directed links.

2.3 Study of Network Models

Regarding a network model, there is agent-based modelling [16],[17] as a framework to integrate multi-layered components, and studies incorporating network models in modelling have advanced. In these studies, a complex doubly structural model [18],[19] that conducts simulation based on a social network and an internal network has been proposed. As an internal network, CDNM expresses knowledge and concept structured using a network structure. As a social network, this network model expresses a society where agents having internal networks propagate and learn the knowledge and concepts of the internal network by adjacent interactions. Therefore, CDNM can express foreign networks in microscopic and macroscopic ways as an integrated model. CDNM works quite well as an excellent framework. On the other hand, the application of this network model to the educational field is for future study on the frontier.

2.4 Position of This Research

As we have seen, related studies are very effective; however, applying the methods proposed by these previous studies are insufficient to estimate the potential effect of teaching strategies including collaborative learning. In this research, we tried to bring about a solution for these issues by using incorporating multi-layered IRT and Bayesian networks. We also proposed a new teaching simulation method that interfaces these network models as CDNM [20],[21].

3. In-Class Learning Process Simulation

In this research, we tried to build a simulation with a class consisting of 30 learners, where it was assumed that five instructions, from X1 to X5, are used when teaching them. This simulation was to estimate what material should be taught, in what order and how many times, until all learners in the classroom could give the correct answer (Fig. 1). In this simulation, we used two criteria, the attainment degree and the average time of teaching. The attainment degree indicates the proportion of correct answer. The degree reaches 1.0 where all learners give the correct answer. The average time for teaching indicates the time until the attainment degree has reached 1, which averages ten simulation sessions. To build the teaching simulation, we used correct answer history data of exams and seating data in the class for model estimations. Correct answer history data for model estimation has two values, correct/incorrect answers, of all 300 learners for five questions that correspond to the instructions taught from X1 to X5.

Figure 2 shows the teaching simulation method based on the complex doubly structural network. There are 30 learners in a class and a teacher who gives them five instructions, X1 to X5. As an internal network of a learner, his/her academic capability, understanding probability and a material structured model are estimated from exam answer data of 300 learners using item response theory and a Bayesian network. From seating allocation and a collaborative learning model, a social network model in the class is estimated. The attainment degree, which is the proportion of correct answer, and teaching time are used as the criteria to estimate the effect of teaching.

3.1 Definition of the Internal Network

The internal network is composed with multi-layers combined the understanding probability model of knowledge according to the academic capability of each learner and the learning material structure model. When certain knowledge is taught, based on the understanding probability model, the understanding probability according to the academic capability of each learner is calculated. As for knowledge items, the understanding probability propagates along with the material struc-
3.2 Understanding Probability Model

When it comes to the understanding probability model of all knowledge that corresponds to the academic capability of each learner, the item parameter is estimated by conducting the marginal maximum likelihood estimate based on the quasi-Newton’s method and the EM algorithm, which is an expectation-maximisation (EM) algorithm for finding maximum likelihood of parameters in statistical models. The ability parameter is estimated by using the empirical Bayes method. By using these estimated values, the understanding probability model is built. Specifically, this estimation is done by using the correct answer history data for model estimation and the package LTM on software R [22]. The result of this estimation is quantified as the form of Ability. The estimated Ability parameter (item characteristic curve), shown in Fig. 3, is set according to the knowledge, and the understanding status for all knowledge of each learner at the point in time before teaching, in order to estimate the understanding probability of knowledge of each learner. Figure 4 organises the ability of the correct answer status of all knowledge and the understanding probability of knowledge, which are set as simulation parameters. The 2PL model for formula 1 was applied in this research.

3.3 The Course Material Structure Model

The material structure model was built by utilising the structure estimation on the Bayesian network. As for model estimation, the correct answer history data for model estimation was used. The result was estimated with the greedy method on the package deal of software R. This was estimated as in Eq. (2):

\[
P(X_1, X_2, X_3, X_4, X_5) = P(X_1)P(X_3|X_1)P(X_4|X_1, X_3)P(X_2|X_1, X_3, X_4)P(X_5|X_2, X_3, X_4).
\]

(2)

The conditional probability was calculated with the package bnlearn of software R by using the model of formula 2. Figure 5 shows a diagram of the conditional probability calculated using Eq. (2).

3.4 Definition of the Teaching Simulation Model

When it comes to the classroom network, in order to build a model, we assumed an all-together (brick-and-mortar) classroom lecture consisting of one teacher and 30 learners, where collaborative learning would be done between each of learners sitting left to right. Learners were allocated according to seating data. If it was found according to correct answer history data that either those learners on the left or those on the right understood the targeted knowledge taught, he/she should conduct collaborative learning when the teacher teaches that knowledge so that the other learners could also understand the knowledge taught.
Based on CDNM consisting of an internal network and a social network, this simulation estimates the progress of understanding status of the learner when teaching is done by following the procedures described in Fig. 6.

3.5 ODD Protocol

Based on overview, design concepts, and details (ODD) protocol, the proposed learning model is described and formulated in Table 1.

4. Experimental Results and Discussion

4.1 Experiment 1: Evaluation of Teaching Strategies

In the experiment, we tried to discuss the issue of what kind of influence teaching strategies could have on learning effects. In this experiment, we move our discussion forwards by applying the following four teaching strategies for the class in which students are seated randomly, and then by comparing the average time of teaching sessions and the attainment degrees. The status varies randomly in this simulation; therefore, ten simulation sessions were conducted for each teaching strategy (TS).

- **TS1** Teacing along with the complex doubly-structural network model
- **TS2** Teaching by selecting items to teach in a random manner
- **TS3** Teaching an item where many learners gave wrong answers
- **TS4** Teaching by moving to next item when all learners understood an item by order of the highest correct answer rate according to each model question

As the result of conducting ten simulation sessions, the average teaching time is shown in Table 2. This result confirmed that learning effects depend on teaching strategies. Where there was no collaborative effect, teaching strategy 1 has the lowest average teaching time. The teaching times increased in the order of teaching strategies 4, 3, and 2. This result confirmed that learning effects depend on teaching strategies. Figure 7 shows the transition of attainment degrees for teaching times. When observed from the viewpoint of the average teaching time, in both teaching strategies 1 and 4, the teaching time was less than 12 times. We can consider that these strategies had higher learning effects. From the viewpoint of the attainment degree, teaching strategy 1 has a tendency where the initial growth was higher than the other strategies. For example, when the attainment degrees after the fifth teaching session are compared with the degree of each strategy, TS1 was 0.70, TS2 was 0.59, TS3 was 0.42, and TS4 was 0.49. Therefore, this shows that teaching strategy 1 had the highest attainment degree. In any of teaching strategies of 1, 2, 3, or 4, the attainment degree did not reach 1. For this reason, in this class, we can see that any of these teaching strategies should be insufficient to have all learners acquire all knowledge items in five teaching times. In other words, if teaching is done one time for every knowledge item, some learners could fall behind in the learning progress. This shows that review or makeup classes are necessary.

4.2 Experiment 2: Evaluation of Collaborative Learning

In the second experiment, preparing three different environments for the lecture model, the left-and-right collaborative learning model, and the group collaborative learning model, we compared the results. The left-and-right collaborative learning model is a model where the seating arrangement is the same as the lecture model and collaborative learning occurs between left and right seats as shown in Fig. 8. On the other hand, the group collaborative learning model is a model where the seating arrangement is grouped in a classroom, and collaborative...
Table 1 ODD protocol table for the proposed learning model.

| Overview | Purpose | To investigate how the learners’ understanding will be changed by teaching styles in a classroom |
| --- | --- | --- |
| | Entities | A teacher, students, sheets, relationships, classrooms |
| | State valuables | Understanding status, knowledge, ability, understanding probability, answer, sheeting position |
| | Scales | A teacher, students, sheets, relationships, classrooms |
| Design concepts | Basic principles | Item response theory, probabilistic reasoning methods, and complex doubly structural model |
| | Emergence | Understanding status of learners through collaboration |
| | Adaptation | Indirect objective-seeking of knowledge with neighbours |
| | Objectives | Average understanding status of learners and teaching time |
| | Learning | Learning knowledge from a teacher and neighbours |
| | Prediction | No prediction |
| | Sensing | Relationships on a seating arrangement knowledge given by a teacher |
| | Interaction | Collaborative learning through transmitting knowledge between neighbours on a seating arrangement |
| | Stochasticity | A conditional probability chart between learning items based on Bayesian network approach |
| | Collectives | Collaboration between students in a classroom |
| | Observation | Understanding status of students in a classroom |

Details

| Initialization | The number of students, students’ ability level of a classroom |
| Input Data | Understanding probabilities of each knowledge based on test data |
| Sub models | Test theory model, probabilistic reasoning model, complex doubly structured model |
| | Agent-based collaborative learning model |

Table 2 The average teaching time in Experiment 1.

| Teaching strategy | Teaching time |
| --- | --- |
| TS1 | 22.5 |
| TS2 | 41.4 |
| TS3 | 32.3 |
| TS4 | 23.4 |

Fig. 7 The transition of attainment degrees for teaching times of teaching strategies 1 and 4 (y-axis: achievement rate, x-axis: teaching times).

We conducted ten simulation sessions. Table 3 shows the average number of teaching of the simulations. In any of environments for the lecture model, the average number of teaching decreases in order of the lecture model, the left-and-right collaborative learning model, and the group collaborative learning model. Therefore, it is obvious that the collaborative learning models has a positive effect on learners more than the lecture model, and the wider the range of collaborative learning is, the more the effect on learners is. On the other hand, the attainment degree did not reach 1 in any of teaching strategies of 1, 2, 3, or 4.

In the group collaborative learning model, teaching strategy 4 has virtually the same effect as the strategy 1 in terms of the average number of teaching times. This result means that teaching strategy 4 with the group seating arrangement, which is the teaching method in order of the highest correct answer rate, is one of the best strategies for a newly-appointed teacher, because she or he has difficulty teaching while understanding their knowledge structure, ability and collaborative relations.

4.3 Experiment 3: Evaluation of Seating Arrangement

The third experiment considered what kind of influence seating arrangements of learners could have on learning effects. In this experiment, preparing four different environments for
the social network, concentrated arrangement and dispersed arrangement, we conducted ten simulation sessions by using teaching strategy 1. Afterward, we compared the results. The concentrated arrangement is a model where learners with high academic capability are gathered in one place. The dispersed arrangement is a model where learners with high academic capability sit next to those learners with low academic capability.

About the left-and-right collaborative learning model, we created particular situations with the concentrated and dispersed arrangements by changing the seating arrangement of learners as shown in Fig. 10, where learners who got all the answers correct were gathered in the upper-left area and the dispersed arrangement model where they were arranged vertically in the centre. On the other hand, we also conducted a group collaborative situation with the concentrated and dispersed arrangements by changing the seating arrangement of learners as shown in Fig. 11.

We compared both situations for discussion. In this experiment, we estimated the academic capability of each learner by using IRT based on the correct answer history of the learner. According to the estimated value, we determined those learners with high academic capability. Determining those learners that have above a certain estimated value to be excellent learners, we structured the concentrated arrangement and the dispersed arrangement by changing the seating arrangement of those excellent learners. As for the average teaching times, the concentrated arrangement was 9.5 times with the left-and-right model and 8.4 times with the group model, while the dispersed arrangement was 7.7 times and 5.6 times as shown in Table 4. The average teaching time in experiment 2, before the arrangement was changed, was 8.2. While the average teaching times increased in the concentrated arrangement, it decreased in the dispersed arrangement. Through this result, we were able to confirm that learning effects vary by making changes in the seating arrangement for learners and the dispersed arrangement could enhance teaching effects.

4.4 Evaluation of the Effects of Grouping according to Ability

The fourth experiment considered the issue of ability classes in a school. Ability classes mean that children are divided up into classes according to their ability levels to be taught. In this experiment, preparing two different environments for ability classes and mixed-ability classes as shown in Fig. 12, we conducted ten simulation sessions by using teaching strategy 1. The environment of ability classes has three classes divided by their ability level of the answer data on online learning. For comparison, the environment of mixed-ability classes is prepared with three classes in which all the learners are mixed by ability randomly as shown in Fig. 12.

As the experimental results, the total number of teaching times in three classes of the lecture model, the left-and-right collaborative learning model and the group collaborative learning model are shown in Table 5. And the results of the average number of teaching times in ability classes are shown in Table 6.

When observed from the viewpoint of the teaching time, the number of teaching times for the ability classes is less than the mixed ability classes in the lecture model. On the other hand, the number of teaching times for the ability classes is more than the mixed ability classes in both the left-and-right collaborative learning model and the group collaborative learning model. The results indicate that ability classes have adverse effects on learners in collaborative learning.

5. Discussion

We utilised the simulation for in-class learning processes considering academic capability, learning material structure, and collaborative relationship. In the first experiment, using four teaching strategies, we quantified the teaching procedure selected by each teaching strategy and the learning effect sta-
The environment of mixed-ability classes has three classes, divided by their ability level of test results on online learning. In a school, the environment of ability classes has three classes and all the classes have 30 learners mixed by ability randomly. The results of the experiment indicate that ability classes have adverse effects on learners in the collaborative learning models, while ability classes are more effective than the mixed ability classes in the lecture model.

According to these experiments, collaborative learning in a group with a dispersed seating arrangement makes more effective than other teaching strategies including the lecture style and the left-to-right collaborative learning style. Furthermore, ability classes in a school possibly have negative effects to learning because they reduce diversity in a class. Heterogeneity between learners on collaborative learning makes all the difference, while homogeneity has the risk to take away diversity from learners and makes collaborative effect fall into decline.

### 6. Conclusion

The purpose of this research was to clarify the actual conditions of understanding of teaching done in a classroom. As a means to do so, we proposed a simulation for in-class learning processes with consideration given to academic capability, learning material structure, and collaborative relationships. We built an internal network by estimating the understanding probability network by the use of IRT and estimating the learning material structure model with the use of the Bayesian network.

Furthermore, we modelled the relationships between the teacher and learners in a classroom as a form of a social network. By interfacing these network models as the complex doubly-structural network model, we were able to model the actual condition of teaching done in a classroom for the first time, and produced a new simulation model for education. With that, by considering the learners’ academic capability, the dependency between knowledge items, and collaborative relationships, we were able to quantify the teaching effects in the classroom and conduct simulations to determine effects. In this research, we were able to acquire four observations through experiments.

1) When different teaching strategies, seating arrangements, and collaborative learning are used, learning effects vary. 2) Group style collaborative learning on dispersed seating arrangements using the doubly structural learning model has the best learning effect, and the second best is the method in order of the highest answer rate. 3) An ability class has negative effect on collaborative learning because they reduce diversity in a class, so homogeneity between learners has the risk to make collaborative effect fall into decline. 4) Whereas, if teaching is done one time for one knowledge item, some learners could fall behind in the learning progress. Reviews should be conducted repeatedly to facilitate the anchoring of the knowledge in a class.

Nevertheless, we have not been concerned about negative effects from unskilful students or misunderstanding, so we need to add the negative effects in the model in our future work. Besides, there are classes that adopt more dynamic collaborative learning approaches where high ability students are allowed to walk around, talk and discuss with other students in their class. This dynamic situation should be considered for our next model.

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