Adopting a Productive-failure Instructional Design in Project-based Learning to Improve Primary Students' Collaborative Problem Solving

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Abstract: The paper reports on an empirical study on adopting an innovative pedagogical design in project-based learning to improve upper primary students' problem solving skills in science learning. A Grade 6 class in a Hong Kong primary school was involved in this study. The findings show that the students produced high group artifacts/projects in problem-solving quality and were positive in facing challenges in their project-based learning process. This indicates that project-based learning with PF instructional design can be an effective way to develop students' problem solving skills.

Introduction

In the digital age, problem solving is one of 21st Century skills critical for preparing students in a global economy and society (Voogt & Roblin, 2012). This is in line with what is advocated in science education in Hong Kong which comprises a core component of the primary school General Studies' curriculum. Science education promotes creativity through the problem-solving process in authentic learning environments supported by digital technologies (The Education Bureau, 2011). However, in practice, science learning, in many cases, is still largely disconnected from learners' daily life and confined to textbook learning (Anastopoulou et al. 2012). Students are passive knowledge receivers resulted from a lack of opportunities to be question askers, inquiry method designers and action-takers. This empirical study attempts to explore an innovative pedagogical design to improve upper primary students' collaborative science learning competency.

Literature

Collaborative problem-solving in science through project-based learning

In science learning, the project-based learning approach aims to involve students in working at real-world problems in small groups and striving for solution options where the teacher acts as a facilitator (Brundiers & Wiek, 2013). Thus, problem solving competency is critical in carrying out the project. Its processes include: exploring and understanding; representing and formulating; planning and executing; and monitoring and reflecting (PISA, 2017, p. 9). In many cases, problem solving involves collaboration, especially in dealing with complex tasks. Collaboration is defined as "the activity of working together towards a common goal" (Hesse, Care, Buder, Sassenberg, & Griffin, 2015, p. 38). Collaborative problem solving requires social and cognitive skills to develop shared understanding, take appropriate action and establish and maintain team organisation to solve the problem (Dillenbourg, 1999). Guided inquiry is advocated in existing collaborative problem solving for young learners, where scaffolding is provided when students encountered learning difficulties to avoid failure in making the inquiries (e.g., Hakkarainen, 2003). However, Kapur (2015) posits that learners are learning from failures. One concern of this study is: can young learners learn better without the scaffolding in their inquiry process?

Productive failure instructional design

Productive failure (PF) is defined as "a learning design that affords students opportunities to generate solutions to a novel problem that targets a concept they have not learned yet, followed by consolidation and knowledge assembly where they learn the targeted concept" (Kapur, 2015, p. 52). PF instructional design involves two phases: (1) students first engage in unguided problem solving activities to elicit their prior knowledge, particularly the failure to solve the problem; and (2) students then use this information to consolidate and aggregate new knowledge after the teacher helps solve misconceptions (Kapur, 2016). The failure stems from the fact that learners are commonly unable to generate or discover the correct solution to the novel problem by themselves; on the other hand, they are able to generate sub-optimal or even incorrect solutions to the problem, the process can be productive in preparing them to learn better from the subsequent instruction that follows. Indeed, in science learning, generating "wrong answers" may help to focus students' attention on the complexities and frustrations of a good investigation plan or design (Hodson, 2014).

This empirical study aims to examine the effectiveness of project-based learning with productive failure (PF) instructional design in improving primary students' collaborative problem solving skills in science learning.

The research question was: Was the project-based learning with PF instructional design effective in improving students' collaborative problem solving skills?

Methods

Research context and participants

This study was conducted in a Grade 6 class with 27 aged between 12 and 13 years' old on the project of "Plants and Environments" in a primary school. Students were classified into four groups. Each group had 6 or 7 members. The school lent an iPad and a laptop to each group. Students could use their own mobile devices as well in their inquiry. Before this study, the students had conducted project-based learning supported by mobile devices for two years, and were familiar with the apps of (1) a social network platform - Google Classroom for groups to document their project-based learning process; (2) a built-in camera on mobile devices for picture taking to collect data; and (3) an augmented reality (AR) App: MKAPS. The AR artifacts were created using the school's AR creation platform (http://mkaps.ar.myprint.asia). Students created a video clip first, and then uploaded it to the AR creation platform to generate a picture. As long as students downloaded the app – MKAPS from Apple Store, they could scan the picture to view the videos.

The project lasted for two weeks. The teacher had over six years' teaching experience and had been involved in the project-based learning programme initated by the school in the past two years. Before conducting this study, the researcher conducted two 2-hour teacher professional development workshops on social constructivist principles and pedagogical models, especially on inquiry/project-based learning and productive failure instructional designs in the school. The researcher also co-designed the project of "Plants and Environments" with the teacher after the two professional development workshops, adopting the PF instructional design.

Project-based learning with PF instructional design on "Plants and Environments"

Because the projected lasted two weeks, the students were suggested choosing two kinds of Rhizome plants to grow, and find out factors that influenced the growth of the plants they chose. In doing so, they needed to work in groups to make their own plans to raise the plants. In order to understand better the factors that contributed to the growth of the plant, they usually prepared two or three plants of the same kind to grow in different conditions, and observed, documented and explained their process of growth.

The project-based learning with PF instructional design consisted of two stages (see Figure 1). Stage 1 was designed for unguided collaborative problem solving activities: (1) Explore and understand: group members explored and gained some understanding of the plants and environments in a field trip to a school farm; (2) Represent and formulate: group members discussed with each other after the field trip to reach a common goal for doing the project; (3) Plan and execute: group members worked out plans for the project and executed them; and (4) Monitor and reflect: group members monitored and reflected on the progress of the project to reach better shared understandings. Stage 2 was designed for consolidating and aggregating new knowledge by solving misconceptions and failures facilitated by the teacher.

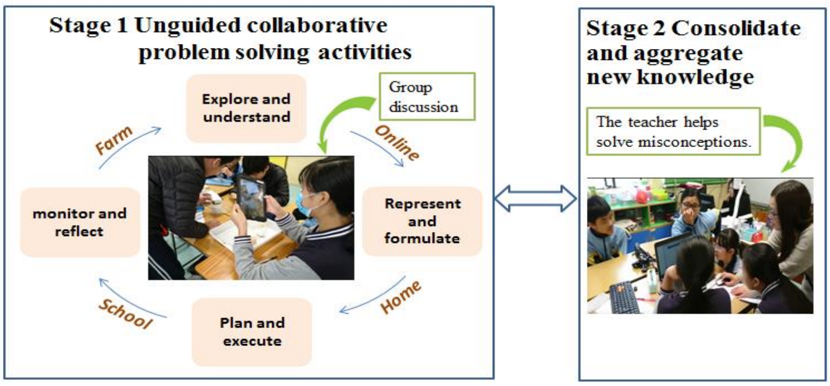

Figure 1. Project-based learning with PF instructional design.

Students in groups explored factors that influenced plant growth in different conditions on their own before learning new concepts followed by the teacher's help in solving misconceptions, from which students consolidated and aggregated the conceptual knowledge. Students in groups investigated problems related to plants and their environments in across different spaces like home, farm, school and online with mobile devices.

Data collection and analysis

Data collection included student artifacts such as pictures or videos captured using mobile devices to document the process of plant growth, searched and downloaded online resources, concept maps, notes related to the plans of the group project, and group created project booklets as final project products. In addition, two focus group post interviews were conducted in order to "hear the participants' voice" through the interactions. The interview items (5 items with follow-up questions) were related to the research aims about collaborative problem skills in the project-based learning. The interview items were reviewed by an experienced researcher. Thus, the interview instrument had its face validity. Each of the interviews consisted of three to four members, and lasted about 35 minutes which was recorded. Further, students' post-reflections were also collected after the project-based learning. The reflections were in the forms of written text and video recordings in Chinese. All the data were submitted to the Google Classroom, some of which were selected and incorporated into the final project product - project booklet. The video recordings were embedded in the booklet in the form of AR picture with a star logo, which could be scanned and accessed. The interviews were conducted in Cantonese. All the recorded data were transcribed from Chinese into English. Finally, pre- and post-domain tests consisting of eight multiple choice items (a, b and c choices) on conceptual knowledge related to plants and their environments were conducted before and after the project-based learning. The items were constructed based on the science learning curriculum.

Mixed data analysis methods were utilised. First, "process-oriented analysis" was adopted in a natural context (Järvelä, Veermans, M., & Leinonen, 2008, p. 305) including on-task analysis and content analysis to understand the process and outcomes of the students' collaborative problem solving skills in the project-based learning. In particular, process-oriented analysis using a multiple-methodological qualitative approach via overlapping and interactive analysis of data between on-task analysis and content analysis offered a more profound understanding of the cases (Song, 2016). On-task analysis in this study was conducted using the framework of the "matrix of collaborative problem solving skills" (PISA, 2017) premised on the evidence-centered design (ECD) framework (Mislevy & Haertel, 2006), in which "assessment is considered a process of reasoning from imperfect evidence using claims and evidence to support the inferences being made about student proficiency" (PISA, 2017, p. 26,).

In this study, the framework of the "matrix of collaborative problem solving skills" focuses on the analysis of student activities in each of the project-based learning task components (vertical): "explore and understand; represent and formulate; plan and execute; and monitor and reflect (PISA, 2017) together with the collaborative components (horizontal) of "establish and maintain shared understanding, take appropriate action to solve the problem, and establish and maintain team organization". The score on each component was given based on the detailed instructions in PISA (2017). Each task contained one or more items to be scored. Each item was coded from zero to a number of categories (0, 1, …categories). The project-based learning task components were coded as (A) Explore and understanding (20 scores); (B) Represent and formulate (25 scores); (C) Plan and execute (30 scores); and (D) Monitor and reflect (25 scores). The collaborative learning components were coded as (1) Establish and maintain shared understanding (45 scores); (2) Take appropriate action to solve the problem (25 scores) and (3) Establish and maintain team organization (30 scores). The collaborative problem solving competency of each group was the result of the matrix ABCD1, ABCD2, and ABCD3. The weighting of the collaborative learning components (1) and (3) were higher because these competencies were closely related to collaborative skills; and (2) was more related to problem-solving behavior within a collaborative context (PISA, 2017).

Content analysis was used to analyze focus group interviews, student post-reflections and project booklets using the matrix of collaborative problem solving as the coding framework. All the data analysis results served for addressing the research question about the effectiveness of project-based learning with PF instructional design. The inter-coder reliability regarding collaborative problem solving competency was assessed by two independent researchers. The Pearson correlation between the two coders was .81. This indicated that the data analysis results were reliable. Finally, descriptive quantitative analysis using SPSS version 24 was conducted to analyze pre- and post-domain tests.

Research results and discussions

Research results

To address the research question: "Was the project-based learning with productive failure (PF) instructional design effective in improving students' collaborative problem solving skills?", the results are presented in three ways: First, overall results of collaborative problem solving skills were presented, followed by the results of pre- and post-domain tests. Finally, the results of one group's collaborative problem solving process were selected in order to evaluate the groups' collaborative problem solving process.

Results of collaborative problem solving competency

The final results of all the groups' collaborative problem solving skills are presented in Table 1.

Table 1. The Results of collaborative problem solving skills in Class 1 and Class 2

Class	Group	*Matrix1	*Matrix2	*Matrix3	Total=100
1	G1	ABCD1=33	ABCD2=19	ABCD3=24	**76**
	G2	ABCD1=28	ABCD2=19	ABCD3=21	**68**
	G3	ABCD1=38	ABCD2=24	ABCD3=25	**87**
	G4	ABCD1=37	ABCD2=23	ABCD3=23	**83**

* *Matrix1 = The project-based task components A, B, C D versus collaborative learning component 1*
Matrix2 = The project-based task components A, B, C D versus collaborative learning component 2
Matrix3 = The project-based task components A, B, C D versus collaborative learning component 3

Table 3 shows that in general the groups' scores of collaborative problem solving skills were high. This indicates that generally speaking, students performed well in the project-based learning with PF instructional design.

Results of pre- and post-domain tests

A difference score for each student between post- and pre-domain tests was calculated. The mean difference of the class was .82. This means that there was comparatively a large change in the students' learning.

Results of a group's collaborative problem solving process

In order to present collaborative problem solving process, one group with six members was chosen randomly. The group chose shallots and mug beans to grow and explored the relationship between these plants and their environments. We selected some of the artifacts created by the group as evidence to demonstrate their collaborative problem solving process under the framework of matrix of collaborative problem solving skills.

"Explore and understand" and "Establish and maintain shared understanding" (A1)

At the collaborative "explore and understand" stage, the students took pictures during their visit to the school farm in the field trip and made reflections after the visit. They paid more attention to the shallot which was the focus of their study and collected detailed materials for their further exploration.

The group members' reflection was quite detailed and in depth. They indicated that they got to know a variety of plants. Two members reported that they learned new knowledge about plants like edible plants and herbs. For example, Member 1 said, "*Plants can help people in various ways. Except being used for food, Li Shizhen used herbal medicine to treat the disease and save people's lives in ancient times. Besides, plants can convert carbon dioxide to oxygen in order to provide fresh air.*". In addition, the members learned how to plant shallots outdoors and indoors. In particular, they took some pictures of shallots in an outdoor garden in order to compare them with what they planted, and identified the differences between them. Thus, at this stage, members reached common understanding of the plants and what topic of the project they planned to work on. They would like to explore whether it was more effective to plant shallots in water than in soil, and what factors might influence the growth of the shallot.

"Plan and execute" and "Take appropriate action to solve the problem" (C2)

In growing the plants, the group members planted shallots in three different living conditions and explored how the environmental factors like sunlight and water influenced the plants' growth. When facing with problems in the project, they would like to look for materials and discuss with their group members to propose solutions collaboratively. In addition, they collected detailed data in order to develop a comprehensive understanding of their experiments (see Figure 2). They took down the data about temperature, humidity and luminosity in three environments, and the growth height of shallots daily. They also summarized the status of the plant growth daily. Moreover, they took notes on the pictures to illustrate the growth process of shallots clearly.

Date	Shallots	Luminosity	Height (mm)	Temperature (℃)	Humidity (%)	Watering Quantity(ml)	Notes
27/2 (1)	a	11	0	14-18	40-85	50	Place it in a plastic cup with wet cotton.
	b	3	0	14-18	40-85	50	Place it in a plastic cup with day cotton.
	c	3	0	14-18	40-85		Place it in a plastic cup with wet cotton.
Analysis: there is no change among three shallots.							
28/2 (1)	a	21	0	14-19	40-83	50	There is no change among three shallots.
	b	6	0	14-19	40-83	50	
	c	6	0	14-19	40-83		
Analysis: there is no change among three shallots.							

Figure 2. Detailed data records of 1G3.

“Monitor and reflect” and “Establish and maintain shared understanding” (D1)

In monitoring the growth of the shallots, the group members focused on comparing the growing situation in three different living conditions: (a) air, water and sufficient sunlight; (b) air and water without sufficient sunlight; and (c) only air, no water and sufficient sunlight. The experiment results (see Figure 3) show that only the shallot in the first living condition (a) began to sprout and grow (indicated with an red arrow), while shallots in other living conditions became dried (c) or the outer layer of the shallot started to fall over gradually (b).

The group members made three conclusions based on their experimental results, and by studying other groups’ experimental results. Firstly, they believed that some kinds of plants could grow well in different living conditions but others could not. They observed the growth situation of the lettuce in another group, and found that it could grow well in the soil and in the water, while their shallot could not grow in water. Secondly, plants could not grow well without photosynthesis. They observed that seedlings of their shallot in the first living condition were green. Also they observed that the lettuce raised by another group in the environment with the air, water and sufficient sunlight was green; by contrast, the lettuce in the environment without sufficient sunlight was light green. Thirdly, water, the air and sufficient sunlight were essential for plant growth. They compared shallots in two other living conditions, as well as the lettuce and radish leaves compared in same the conditions by other groups, and found that none of them could grow healthily. They synthesized their findings as well as the findings from other groups, and drew a comprehensive conclusion to solve their problems successfully after the teacher’s facilitation at the end of the project.

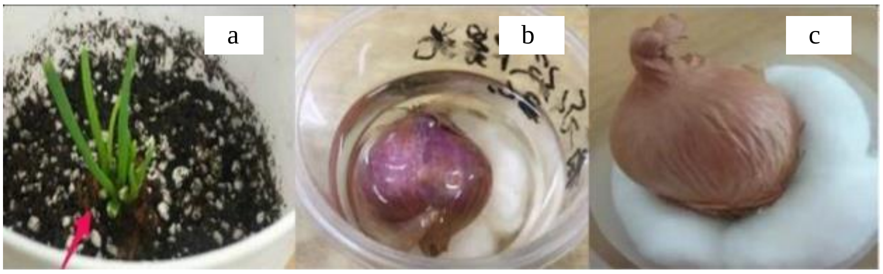

Figure 3. a, b and c. Shallots in three different living conditions from left to right.

“Monitor and reflect” and “Establish and maintain team organization” (D3)

In the group reflections, the members made more detailed reflections after the project-based learning. They expressed their views and shared them with other groups. They also made video clips and created the AR artifacts using the AR app adopted in this project to reflect what new knowledge they learned in the project-based learning. They reported that shallots could be planted in water. But shallots needed to be transplanted to the soil because they needed to get nourishment from the soil. They also knew that different kinds of plants needed to live in different environments. For example, mung beans could grow faster in an environment lacking abundant sunlight, and shallots could not grow well in the water but lettuce could. Besides, they understood in more depth about the importance of photosynthesis for healthy growth of plants. Most importantly, through this collaborative project-based learning activity, they realized teamwork was vital for the success of their project. Moreover, even though they failed to grow the shallot in water, they obtained ample evidence to solve their problems consolidated by the teacher, and did not feel frustrated or disappointed about the failures. They mentioned that the sharing of the group project work in the class and the teachers’ facilitation and instruction was useful for them to solve their misconceptions and get deeper understanding of the concepts related to plants and their environments. Thus, they reported that they did learn from failures.

The final project booklet created by the members was presented logically and scientifically from how to explore and understand plants and their environments in a field trip to a school farm to what problems they focused on, how to plan and work out the problems, then to making what they have learned (deep reflections) at the end of the report (see Figure 4). What was most impressive about the group was that at the end of the project booklet, they compared the features of the shallots growing outdoors that they observed on the farm with the one they grew indoors in soil, and identified the differences between them. They also consolidated their findings by observing other group's project of growing lettuce indoors. This suggests that the group advanced their conceptual knowledge about plants and their environments in the project-based learning. Throughout the group's booklet, the AR artifacts (video clips) that the members created were embedded in the booklet (see Figure 4 with a star logo for an example). By doing so, the project booklet was augmented and enriched by video clips. The members in the group were motivated to produce the best work they could and deepened their knowledge. They reported that the artifacts, especially the project booklet they created made them feel strong ownership of their own learning and would like to do more such kind of studies in future.

Figure 4. Selected picture from the Project Booklet embedded with AR artifact

To conclude, the findings of this study indicate that productive-failure instructional design is conducive to developing primary students' collaborative solving skills in science learning.

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