# Instructional Design and Evaluation of Science Education to Improve Collaborative Problem Solving Skills

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**Abstract:** Collaborative Problem Solving (CPS) skills are essential in education and in the 21st century workforce. CPS involves two main domains: the social domain (e.g., communication or cooperation) and the cognitive domain (e.g., domain-specific problem-solving strategies). As well as scientific knowledge, communication skills, problem-solving creativity, and motivation for learning and inquiry are also required in science education. In this article, a science lesson was designed and integrated with ICT for development of students' CPS skills. We assessed changes in students' CPS awareness, and acquisition of related knowledge, before and after the lesson. Results showed CPS awareness on the cognitive domain and acquisition of knowledge were significantly improved. We also examined correlations between students' CPS awareness, knowledge acquisition, and learning motivation. The results showed significant correlation between students' awareness of CPS and their acquisition of related knowledge.

**Keywords** Collaborative problem solving, Science education, Instructional design, High school education

## Introduction

Effective science education is important for students who want to be competitive in the global knowledge society. Different from subjects which learn about conventions in human society, in science education, students learn about the relationship between nature and human beings. Therefore, as well as knowledge and facts, students are also excepted to be armed with skills of communication, problem-solving creativity, and thinking (Carlgren, 2013).

Problem solving is a key factor in science education. Problem solving methods enable students to learn by working on problems, through processes, such as observing, analyzing, interpreting, and formulating conclusions, etc. (Kirtikar, 2013). It is accepted that students should develop the ability to construct understanding by collaborating with others, so that they will better understand one another, and that they will reason with others to generate, and make sense of the processes they use to tackle scientific questions and applied problems (Hogan, 1999).

In this regard, Collaborative Problem Solving (CPS) has shown great promise in learning science, since CPS includes following potential advantages over individual problem solving: effective division of labor; incorporation of information from multiple perspectives, experiences and sources of knowledge; and the possibility to enhance creativity and quality of solutions through mutual feedback (OECD, 2017). However, student groupings may not automatically create collaboration without teacher support (Karakostas and Demetriadis, 2011), especially when students have not yet developed effective communication, cooperation, and problem-solving skills (Gu, 2015).

### Collaborative Problem Solving

PISA 2015 defined CPS competency as "the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and efforts to reach that solution" (OECD, 2017). In this definition, the word "agent" refers to either a human or a computer-simulated participant. In both cases, it is obvious that the points of CPS will be building and maintaining a shared understanding, and then establishing how individual knowledge and skills can contribute to reaching the solution.

CPS is combined with social and cognitive domains. The social domain, which mainly refers to "collaboration" required in managing the contributions of individuals (Care et al., 2016). Hesse et al. (2015) defined collaboration as the activity of working together towards a common goal, made up of elements including exchanging ideas, agreed division of labor, and active and insightful participation.

And the cognitive domain, which refers to "problem solving", is the activity of perceiving a discrepancy between a current state and a desired goal, and finding or creating a solution to achieve that goal (Hesse et al., 2015).

According to the 2015 PISA Framework, four problem-solving processes are provided in the cognitive aspect. First, identifying the problem. Understanding the problematic situation by analyzing initial information and hidden information about the problem. Second, integrating the information. Selecting and organizing the information, and integrating it with prior knowledge by using graphs, tables, symbols, and words to represent the information, and then formulating hypotheses by identifying the relevant factors of the problem. Third, developing and acting on a plan. Clarifying the goal of the problem, setting any sub-goals, and developing a plan to reach the goal state. Executing the plan that was created is also a part of this process. Fourth, monitoring steps in the plan to reach the goal state, and reflecting on possible solutions and critical assumptions (OECD, 2017). In CPS, problem-solving processes should be performed concurrently with a set of collaborative processes.

Therefore, we integrated the collaboration process and problem-solving process to design tasks for 12th grade students in senior high school in Japan. This study aims to ascertain the effectiveness of such instructional design in science education. Two perspectives were analyzed to demonstrate the effectiveness: the change of learning performance in relation to science knowledge, and the change of CPS awareness, before and after the lesson.

## Methodology

### Design and Procedure

This study took place in a twelfth-grade science class at a public senior high school in Japan. Participants were 36 students aged from 17 to 18 years old, among which 20 (55.6%) were female, and 16 (44.4%) were male.

Before the lesson, students accepted a pre-questionnaire to check their prior awareness of CPS when they take their usual science lessons, and then a pre-test to check their prior knowledge of the related knowledge.

The theme of the science lesson was *Limnic Eruption*, which was based on a natural disaster that happened in 1986, and was related to knowledge of chemistry and geography, and also had a great impact on the ecosystem. We designed this lesson with reference to a related project carried out by Japan Science and Technology Agency (JST). The design was conducted in two continuous lessons over 100 minutes. Students were asked to think of a series of questions to find out the mechanism of limnic eruption, and to clarify the relationship between the environment and human beings.

After the lesson, the post-questionnaire and post-test were implemented to assess the motivation for science learning, and establish awareness of CPS, to see if related knowledge was improved during learning.

Hesse et al. (2015) have proposed a framework for CPS process following a PISA-like process. Based on this framework, we designed problem-solving activities integrated with the *Moodle System* (**Fig.1**).

### Data Collection

Data from 27 students (75% response rate) were collected from pre-and post-test and pre-and post-questionnaire concerning students' awareness about, and how to use, CPS skills in their lessons (Questionnaire 1). A post-questionnaire concerning students' motivations for their science learning was conducted after the lesson (Questionnaire 2). Both questionnaires were rated on a five-point Likert scale ("strongly disagree = 1" to "strongly agree =5"). Free text space was also provided to collect the students' individual reflections in Questionnaire 2. The Cronbach's alpha value for all items in both questionnaires was over 0.90, indicating good reliability in internal consistency.

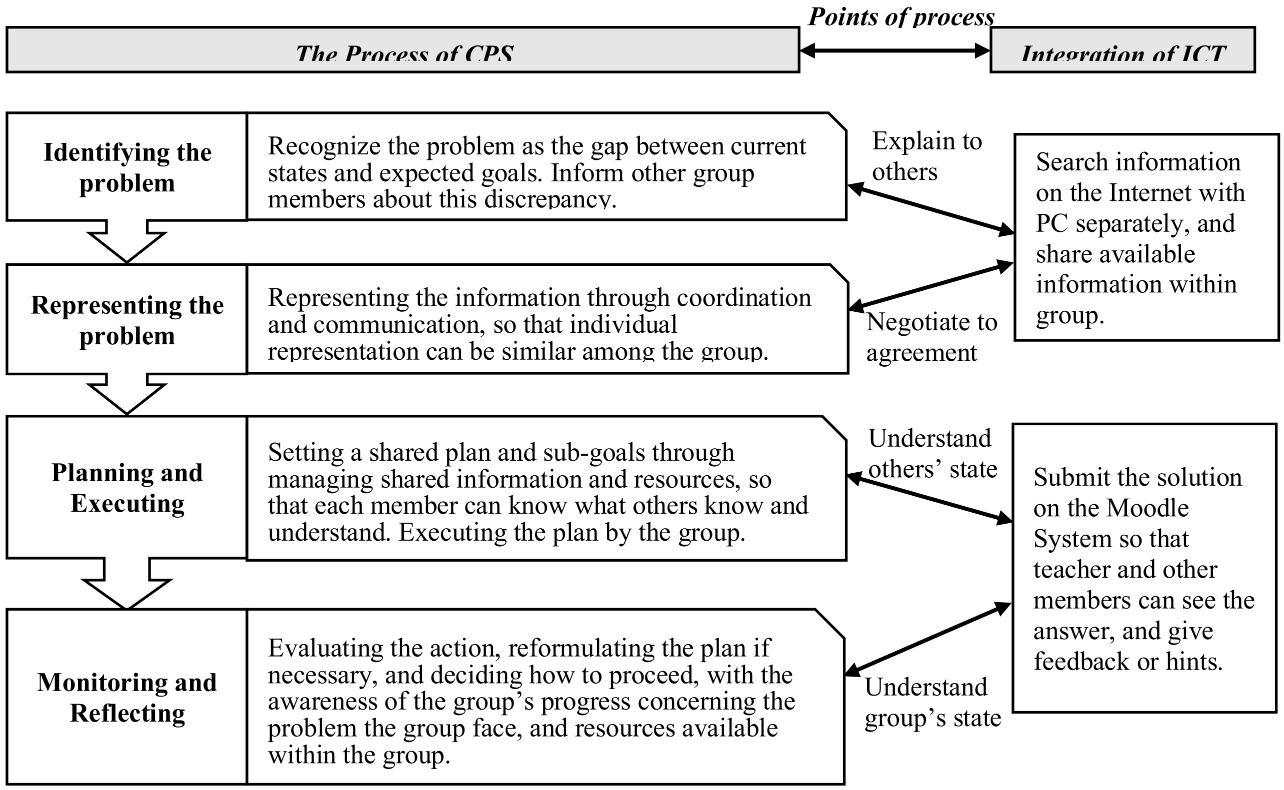



**Fig.1** The process of collaboration problem solving integrated with ICT

## Results and Discussion

### Knowledge Acquisition

The pre- and post-test consists of 6 questions (full marks 6) about the formation mechanism of carbon dioxide, and the impact of the disaster on the ecosystem. We used the Wilcoxon signed-rank test to assess the significance of pre- and post-tests concerning students' acquisition of related knowledge.

According to **Table 1**, the mean value improved from 2.44 (1.28) to 4.07 (1.36), and the significance value is 0.00 (< 0.01), which indicates that there are significant differences in the change of their acquisition of related knowledge before and after the lesson.

| Test | Mean | SD | Median | \|Z\| | p value |
|---|---|---|---|---|---|
| Pre test | 2.44 | 1.28 | 2.00 | $3.56^{***}$ | 0.00 |
| Post test | 4.07 | 1.36 | 5.00 | | |

N = 27; $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

**Table 1** Wilcoxon signed-rank test results of pre-test and post-test

### Collaborative Problem Solving Awareness (Questionnaire 1)

The Wilcoxon signed-rank test was used to assess the significance of the change in pre-and post-Questionnaire 1 concerning students' awareness about whether and how to use CPS skills in their lessons. The scales are used in Questionnaire 1 on Collaborative Problem Solving with reference to Hesse et al. (2015). The Questionnaire 1 consists of two levels, *social skills* and *cognitive skills*, containing 5 scales and 17 items. The contents of scales are listed below.

*Social skills level*

Participation: Actively participate in the class, attach importance to the opinions of others, and always ask others about what they don't understand. Perspective taking: Integrate contributions from others into their own thoughts and actions. Reconsider problems. Social regulation: Recognize the diversity of group members, and negotiate with members until find out the matching solution.

*Cognitive skills level*

Task regulation: Analyzing a problem, setting clear goals, seeking various solutions of complex situation. Learning and knowledge building: Integrating knowledge among other fields or subjects, organizing knowledge and reflecting.

At first, we accessed *Cognitive skills level* by comparing pre-post Questionnaire 1 items on *Task Regulation* (Q10~Q13) and *Learning and Knowledge Building* (Q14~Q17). The results are presented in **Table 2**.

With respect to *Task Regulation*, the mean score was from 12.52 to 14.41 ($|Z| = 4.26$, $p < 0.01$), which reveals that there exists a significant difference in the improvement of awareness of task regulation. Therefore, it is clear that students improved their awareness of problem analysis, target setting, tendency to seek various solutions. And with regards to *Learning and Knowledge Building*, the mean score is significantly improved from 12.89 to 14.33 ($|Z| = 4.26$, $p < 0.01$), which means students have improved their awareness of their knowledge integration and reflection.

One possible reason is that it is effective for students to be provided with a detailed explanation, rather than be given answers directly (Webb, 1995). According to Webb, a detailed explanation can provoke the explainer to reorganize the problem and information, reconstruct their understanding, ideas, and concepts for problem.

Regarding *Social skills level,* mean score concerning *Participation* (Q1~Q3) is from 10.44 to 11.19 ($|Z| = 1.48$, $p > 0.1$), *Perspective Taking* (Q4~Q6) is from 11.89 to 12.37, ($|Z| = 0.68$, $p > 0.1$), *Social Regulation* (Q7~Q9) is from 9.59 to 10.70 ($|Z| = 1.36$, $p > 0.1$), however, no significant differences were found in all scales.

| Level | Scale | Mean (SD) | | Median | | \|Z\| | p |
|---|---|---|---|---|---|---|---|
| | | pre | post | pre | post | | |
| *Social skills level* | *Participation* | 10.44 (2.99) | 11.19 (2.59) | 11.00 | 12.00 | 1.48 | 0.14 |
| | *Perspective taking* | 11.89 (3.34) | 12.37 (3.36) | 12.00 | 13.00 | 0.68 | 0.50 |
| | *Social regulation* | 9.59 (2.74) | 10.70 (2.33) | 9.00 | 11.00 | 1.36 | 0.18 |
| *Cognitive skills level* | *Task regulation* | 12.52 (2.10) | 14.41 (1.89) | 12.00 | 14.00 | $4.26^{***}$ | 0.00 |
| | *Learning and knowledge building* | 12.89 (2.52) | 14.33 (2.51) | 12.00 | 15.00 | $2.25^{*}$ | 0.02 |

N=27; $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

**Table 2** Scales and Wilcoxon signed-rank test results of CPS awareness (Questionnaire 1)

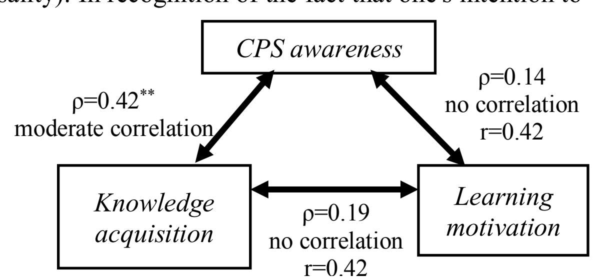
## The Relationship among CPS Awareness, Knowledge Acquisition, and Learning Motivation

In order to further explore the mutual effects among awareness of CPS, knowledge acquisition, and individual motivation for science learning, and also to find out potential factors that could affect the cultivating of CPS skills, we used Spearman's Rank Correlation Coefficient to analyze the correlation among the difference of pre-post Questionnaire 1, and the difference of pre-post tests and Questionnaire 2.

In Questionnaire 2, we used 6 scales developed by Sakurai (1985), and the contents of the scales are listed below.

Challenge: Tendency to take on more difficult tasks than can be solved by oneself currently. Curiosity: Tendency to engage with themes and solve tasks like this lesson. Mastery: Motivation to achieve the goal to completion. Perceived locus of causality (Internal causality & External causality): In recognition of the fact that one's intention to perform a task is caused by an individual/environment. Endogenous-exogenous attribution: Performing a task is treated as the goal or as a means. Enjoyment: Enjoyment of learning.

As shown by the results of the analysis presented in **Fig. 2**, the ρ value between CPS awareness and knowledge acquisition is 0.42, and the significant value is 0.03 (less than 0.05), which indicates that there is significant moderate positive correlation between them. However, there is no significant difference between motivation for science learning and the other two items.




$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

**Fig. 2** Correlation among CPS awareness, knowledge acquisition, and learning motivation

*Correlation between CPS Awareness and Acquisition of Knowledge*

Regarding the improvement of *CPS awareness* and *learning performance*, there are weak positive correlations among improvement of learning performance with some scales of CPS, which is *participation* ($\rho = 0.355$, $p < 0.1$), *perspective taking* ($\rho = 0.395$, $p < 0.05$), *social regulation* ($\rho = 0.331$, $p < 0.1$), and *learning and knowledge building* ($\rho = 0.361$, $p < 0.1$). It indicates that, when students' awareness about participation, perspective taking, social regulation of *social skills level*, and learning and knowledge building of cognitive skills level, the value of variable x is large, and in the case where the value of variable y is large, which is called positive correlation, is higher, their improvement of learning performance will be higher after the lesson. On the other hand, students' abilities to acquire knowledge may also affect their awareness of CPS. However, in terms of *task regulation*, although it has been proved to be significantly improved after the lesson, it shows no correlation with learning performance.

| | ***CPS awareness*** | | | | |
|---|---|---|---|---|---|
| | ***Social skills level*** | | | ***Cognitive skills level*** | |
| | *Participation* | *Perspective taking* | *Social regulation* | *Task regulation* | *Learning and knowledge building* |
| ***Knowledge acquisition*** | 0.355* (0.069) | 0.395** (0.042) | 0.331* (0.092) | 0.111 (0.583) | 0.361* (0.065) |

ρ(Sig.); N=27; $^{***}$p<0.01, $^{**}$p<0.05, $^{*}$ p<0.1

**Table 3** Spearman's Rank Correlation Coefficient between *CPS awareness and Knowledge acquisition*

*Correlation between CPS Awareness and Learning Motivation*

Concerning the *social skills* level of CPS awareness, there is significant weak positive correlation between *perspective taking* with *external causality* ($\rho = 0.382$, $p < 0.05$), *exogenous attribution* ($\rho = 0.385$, $p < 0.05$), and *enjoyment* ($\rho = 0.340$, $p < 0.1$), which means that if students start their inquiry with higher extrinsic motivation or more enjoyment, they tend to integrate contributions from others into their own thoughts and actions more easily.

As for *cognitive skills* level, there is significant difference in moderate positive correlation between *learning and knowledge building* regarding *curiosity* ($\rho=0.432$, $p<0.05$), and *enjoyment* ($\rho=0.415$, $p<0.05$), and weak positive correlation between *learning and knowledge building* and *challenge* ($\rho=0.331$, $p<0.1$). So, it can be inferred that, if students feel the task is challenging and enjoyable, and they show their curiosity and motivation to tackle such problems, or more difficult ones, their learning and knowledge building skills will be benefit from this process.

There is no significant difference in any scale between motivation for science learning and individual performance.

| | | | ***CPS awareness*** | | | | |
|---|---|---|---|---|---|---|---|
| | | | ***Social skills level*** | | | ***Cognitive skills level*** | |
| | | | *Participation* | *Perspective taking* | *Social regulation* | *Task regulation* | *Learning and knowledge building* |
| ***Learning Motivation*** | *Challenge* | | 0.080 (0.692) | 0.188 (0.347) | 0.006 (0.976) | 0.146 (0.469) | 0.331* (0.092) |
| | *Curiosity* | | 0.161 (0.423) | 0.207 (0.300) | 0.228 (0.252) | -0.070 (0.729) | 0.432** (0.024) |
| | *Mastery* | | 0.059 (0.770) | 0.061 (0.763) | 0.213 (0.287) | -0.061 (0.762) | 0.190 (0.344) |
| | *Perceived locus of causality* | *Internal causality* | -0.076 (0.706) | 0.231 (0.246) | 0.038 (0.850) | 0.279 (0.159) | 0.210 (0.292) |
| | | *External causality* | 0.283 (0.152) | 0.382** (0.049) | 0.206 (0.302) | -0.040 (0.842) | 0.256 (0.198) |
| | *Endogenous -exogenous attribution* | *Endogenous attribution* | 0.055 (0.785) | 0.184 (0.358) | 0.073 (0.718) | 0.073 (0.717) | 0.304 (0.124) |
| | | *Exogenous attribution* | 0.153 (0.448) | 0.385** (0.047) | -0.022 (0.912) | 0.019 (0.924) | 0.164 (0.413) |
| | *Enjoyment* | | 0.281 (0.156) | 0.340* (0.083) | 0.218 (0.274) | 0.262 (0.187) | 0.415** (0.031) |

ρ(Sig.); N=27; $^{***}$p<0.01, $^{**}$p<0.05, $^{*}$ p<0.1

**Table 4** Spearman's Rank Correlation Coefficient between CPS awareness and learning motivation

## Conclusions and Future Work

In this study, we designed a science lesson to improve students' collaborative problem solving skills. The theme used in the lesson was based on a real case of disaster, which is related to their chemistry, geography, and biology knowledge. It was expected that students would tend to attach importance to the power of science, by which they can solve real problems related to human beings worldwide.

To ensure collaborative activities were carried out more effectively, it was necessary to make students aware of each group member's state of understanding, and the progress of the whole group, so that the group could reach agreement about the solution through the negotiation. To achieve that, we used the Moodle System to help students understand the state of others, and to allow the teacher to understand the state of each group. As for results, the awareness of CPS and acquisition of related knowledge, were improved. We also analyzed the correlation between the questionnaires and tests, and found that their improvement of CPS awareness is correlated with knowledge acquisition.

In order to offer more detailed reasons for these results, a specific classroom observation for students' behavior and utterance using learning analytics(e.g, Ogata et al., 2015; Yamada et al., 2017) should be undertaken, which will be our future work. In the present study, we have assessed the awareness of CPS skills using questionnaires, so a further challenge will be to assess their improvement of CPS skills.

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