Collaborative Problem Solving-based STEM Instructional Design based on Learning Analytics

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出版情報：Kyushu University, 2021, 博士（教育学）, 課程博士
バージョン：
権利関係：

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Li Chen

Acknowledgments

I still remember the first time I met my supervisor, Prof. Masanori Yamada, in the seminar. He looked at me and asked, “Who are you?” This unexpected question made me more nervous. Another thing that I have not expected is that I have stayed in this tense and strict laboratory for six years.

Prof. Yamada has been an ideal teacher, mentor, and dissertation supervisor. He always offers valuable guidance and continuous encouragement with a perfect blend of encouraging and motivating, whether in my study and life. Prof. Yamada has taught me what research is, how to do research, think on my own, and insist on the things I pursue. There are many kinds of fortune in life, and meeting a mentor is one of them. Although the tasks are heavy and the conditions are strict in the Yamada Lab, I have enjoyed my time in this laboratory. I am extremely grateful that Prof. Yamada has accepted me as his student and continued to have faith in me over the years.

I would like to express my earnest gratitude to my sub-supervisors, Prof. Satoru Tanoue and Prof. Hiroshi Kume. Prof. Tanoue and Prof. Kume have given me careful and valuable guidance and suggestions regarding my research and this dissertation. They spent a lot of time and energy helping me complete my dissertation and inspired me a lot. This dissertation would not have been possible without my supervisor and sub-supervisors’ guidance and help.

I am fortune to participate in the JST AIP project, which provided me great opportunities to conduct other important researches. I would like to thank Prof. Atsushi Shimada’ for his kind support and guidance during this project. I also would like to acknowledge Assistant Prof. Min Lu and Mr. Hiroyuki Watanabe for collaborating with and providing valuable suggestions on my research in the AIP project.

I gratefully recognize the help of the members in Yamada Lab, Hao Hao, XueWang Geng, YuFan Xu, Satomi Hamada, and XuanQi Feng. They always gave me many valuable suggestions on research so that my study can be continuously improved and also provided great help and support in my life.

I would like to thank the principal, teachers, and students who generously took the time to participate in my experimental practice and make this research possible. I would like to express my gratitude to Mr. Hirokazu Uemura, Mr. Koichi Inoue, and the students in Fukuoka Prefectural Itoshima High School, Mr. Nobuyuki Yoshimatsu and the students in Tomeikan Senior High School, and Ms. WeiFeng Wang and the students in Shanghai Aurora Foreign Language Middle School.

In addition, I would like to take this opportunity to thank my good friends. First, I want to thank my friend, Yi Wan. I deeply admired her rich knowledge, the large amount of information, and enough patience, which has brought great help to my research and life. I hope she will continue to use her powerful information collection skill and social skill to help others.

Secondly, I would like to thank the few friends who supported me in pursuing my research. My best friend, HuiYuan Hu, who obtained her Ph.D. in the United States, is the only one who understands my pursuit. She always provides continuous and unconditional support and encouragement for me, even we haven’t had the opportunity to see each other for seven years. Chen Shao and HuiPing Shao have similar interests and appetites with me, so traveling with them and talking to them were the most fantastic experiences. I’m grateful to them for always encouraging me with food and travel plan to inspire me to graduate earlier.

Finally, I would like to thank the people who love me the most in the world: my father, mother, and grandma. My father is a typical Chinese father who is not good at words. When he was angry with me, the biggest punishment he could figure out for me is “cooking the cheapest food for me every day.” My mother and grandma are the two greatest women in my life. I am grateful to them for their understanding and support for me. They may not understand what a Ph.D. means for me, but they still choose to believe that the value of my pursue and my ability exceed missing me and the pain of temporary separation.

In the end, I would like to thank my dog, Tira. Thank her for her pursuit of high-quality dog food, which motivates me to work hard; thank her for staying with me and treating me as the most important person in her little world, until she met my father.

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1.1.1 Definition of collaborative problem solving

In the 21st century, basic knowledge and skills of core academic subjects (such as English, mathematics, science) and applied skills (such as professionalism/work ethic, oral and written communications, teamwork/collaboration, and critical thinking/problem solving) are considered imperative to a successful workforce (Casner-Lotto & Barrington, 2006).

A problem occurs when an individual has a goal but is unaware of the ways to achieve it. The definitions of problems and problem solving differ based on the solvers' beliefs, knowledge, and theoretical goals (Frensch and Funke, 1995). However, all the definitions of problem solving suggest the same process. Frensch and Funke (1995) indicated that the problem begins with a given state, which is the knowledge problem solver has about the problem, and ends with the desired goal state. Between the given state and the goal state, there are many barriers—such as lack of knowledge or effective strategies—that the problem solver must overcome by using some available tools and conducting admissible actions.

Based on the above generally accepted definitions of "problem" and "problem-solving," PISA assessment framework from 2003 to 2012 focused on the assessment of problem-solving competencies. This emphasized the individual capacity to use cognitive processes to understand and solve problems where the solution is not immediately obvious. The PISA 2003 assessment framework only includes the cognitive dimension in its definition of problem solving (OECD, 2003); in contrast, the PISA 2012 assessment framework highlights the affective component, real situations, and the cross-disciplinary contents and subjects (OECD, 2012). Therefore, according to the revised framework, problem-solving competency involves more than the simple reproduction of domain-based knowledge. It includes integrating cognitive, practical, and thinking skills and affective dimensions required to solve unfamiliar problems encountered in real life.

As an active, learner-centered instructional approach, problem-based learning (PBL) is often implemented to facilitate learning through experience by solving real-life problems (Savery, 2006). In PBL, the problems are usually complex and ill-structured; this requires learners to share their existing knowledge and discuss with other learners, seek and manage relevant information, and construct arguments to support their solutions (Lu, Bridges, & Hmelo-Silver, 2014). Problems in the real world are ill-structured; therefore, a critical skill in PBL is identifying the problem and setting parameters on the development of a solution, which is the core of the problem solving, through a series of activities such as collaboration, analysis, self and peer assessment, and reflection (Savery, 2006).

Moreover, students entering higher education or preparing for employment are expected to be equipped with these skills and collaboratively make decisions and generate ideas to solve complex problems. Therefore, collaborative problem solving (CPS) skills are critical for success in the 21st-century workforce (Hesse, Care, Buder, Sassenberg, & Griffin, 2015).

In PISA 2015, the assessment framework highly emphasizes collaboration skills, which include multiple levels such as individual and group levels. In collaborative activities, group members put collective efforts to reach a common goal; the outcome may be greater than the sum of outputs from individual members (Nokes-Malach, Richey, & Gadgil, 2015). Collaboration for problem solving provides potential advantages over individual problem solving; this includes effective division of labor; incorporation of multiple perspectives, experiences, and sources of knowledge; and enhanced creativity and quality of solutions through mutual feedback (OECD, 2017).

The PISA 2015 assessment framework proposed the incorporation of CPS competency and defined it 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). CPS involves individual’s cognitive processes when solving problems that are integrated with the social dimension. The cognitive process of an individual is internal and difficult to observe; however, it can be evident in the interactions between individuals with systems or other people in the group. For example, cognitive processes can be inferred and analyzed based on the individual’s conduct, actions, communications, or negotiations with other members, and the solutions the individual produce. In this regard, the CPS focuses on making observable the cognitive processes during the collaboration. CPS can be assessed through individuals’ exploration processes, strategies used during the problem solving and communication processes, the quality of the communication, the way the individuals represent the problem, and finally, the knowledge acquired (OECD, 2017).

Similar to the PISA framework, Hesse et al. (2015) stated that CPS skills could be analyzed in classroom environments where social and cognitive skills were measurable and teachable. They proposed a conceptual framework of CPS that follow a PISA-like sequential process. Hesse et al. defined CPS as "a joint activity where dyads or small groups execute several steps in order to transform a current state into a desired goal state" (Hesse et al., 2015, p. 39). OECD’s definition of CPS emphasized collaboration, which is sharing the understanding and effort required to reach that solution. Hesse et al. focused on problem solving as a part of the collaboration process. In both these definitions, the observation or development of CPS skills is at an individual level or a group level, and the point of CPS is to make cognitive process observable during collaboration.

CPS discusses two dimensions—social and cognitive. The former refers to collaboration and the latter refers to problem solving (Hesse et al., 2015). According to Hesse et al., there are three important elements in the collaboration dimension: communication, cooperation, and responsiveness. Communication includes sharing knowledge or ideas with other collaborators to improve understanding. Communication also requires understanding the problems and the contents through collaboration. Cooperation is a component within collaboration, which is primarily the division of labor during a task. In CPS, cooperation involves the subdivision of tasks based on the planning and analysis of the problem. Responsiveness means active and insightful participation in collaboration. Generally, in collaborative learning, learners conduct and regulate their activities regarding a particular task or problem with others. The contributions by learners mutually build upon and affect each other, which means one's action might be completed or improves by another.

In problem-solving activities, students need to identify the discrepancy between the current and the expected state and seek solutions to achieve the latter. Problem solving is a cognitive process involving certain mental and behavioral processes (Hesse et al., 2015; OECD, 2015). In CPS, learners need to share their knowledge or understanding of the problem by interpreting the connections between each element, causal relationships of the problem, and the method or solution. These processes can be observed through collaboration, which makes CPS different from individual problem solving.

In CPS, students are expected to solve complex problems that require different information and resources and are difficult to solve by individuals working alone (Care, Scoular, & Griffin, 2016). In other words, students' collaborative and cognitive processes collectively influence CPS skills development (Gu, Chen, Zhu, & Lin, 2015). Several studies indicate the effectiveness of integrating CPS learning into instructional design. Through CPS activities, students acquire knowledge and skills, which they apply to solve ill-defined problems (e.g., Gu et al., 2015). Moreover, students' learning performance would benefit significantly from CPS under teachers' guidance or scaffolding (Lin, Yu, Hsiao, Chang, & Chien, 2020; Raes, Schellens, De Wever, & Vanderhoven, 2012;). In CPS, students can learn specific content, knowledge, or strategies related to the problems; concurrently, they can learn how to collaborate and communicate with other members (Hesse et al., 2015). Therefore, in this study, CPS is adopted as the main approach. The goal of CPS in this study is to help students develop the knowledge and skills to identify the gap between the current state of the problem and the expected state and devise a solution to fill the gap. Students are expected to find the reasons and evidence to support the proposed solutions rather than finding the correct answer for the problem.

1.1.2 Collaborative problem solving skills

In Hesse et al.'s framework of CPS, two broad levels, social skill and cognitive skill, were proposed based on the PISA assessment framework. The descriptions of each element and sub-skills of CPS are summarized according to Hesse et al.'s CPS framework (**Table 1**).

Table 1 Descriptions of CPS skills

Dimension	**Sub-skill**	**Description of sub-skill**	**Element**	**Description of element**
Social skill	*Participation*	Engagement with the tasks, the extent to which they attach importance to others' opinions and interact with others.	Action	The activities in the collaborative environment. For example, learners conduct activities in familiar or unfamiliar contexts actively.
			Interaction	Responding to others' contributions and interact with others during the collaborative activity.
			Task completion	Conducting and completing a task or part of a task by attempting different strategies.
	Perspective Taking	Ability to integrate contributions from others into their thoughts and reevaluate problems.	Adaptive responsiveness	Accepting or adapting the contributions of others
			Audience awareness	Awareness of how to adapt behavior to increase suitability for others
	Social Regulation	Strategy of recognizing the diversity of group members and negotiating with members until mutual solutions are	Negotiation	Achieving a resolution or reaching a compromise
			Self-evaluation	Recognizing one's strengths and weaknesses
			Transactive memory	Recognizing the strengths and weaknesses of others
			Responsibility initiative	Assuming responsibility for ensuring parts of the

		identified.		task is completed by the group
Cognitive skills	*Task Regulation*	Ability to analyze the problem, manage resources, set clear goals, collect information, and seek various solutions to complex situations.	Problem analysis	Analyzing and describing a problem in familiar language
			Sets goals	Setting a clear goal and sub-goals for a task
			Resource management	Managing resources or people to complete a task
			Flexibility and ambiguity	Accepting or adapting ambiguous situations (for example, multiple solutions for a problem)
			Collects elements of information	Exploring and understanding elements of the task, what information is useful, and how to use this information
			Systematicity	Implementing possible solutions to a problem and monitoring progress
	Learning and Knowledge Building	Ability to identify relationships between pieces of information, integrate knowledge from other fields or subjects, monitor outcomes, reflect on processes.	Relationships	Identifying relationships between and among elements of knowledge.
			Rules: "If…then"	Setting a plan based on the understanding of the cause and effect of knowledge.
			Hypothesis "what if…"	Setting and testing hypotheses using a "What if…?" approach.

According to Hesse et al. (2015), first, there are three aspects contained in social skills: *Participation, Perspective Taking, and Social Regulation.*

Participation refers to the observable action during a collaborative activity. In Hesse et al.'s framework, three elements are included in participation: action, interaction, and task completion.

Action includes the activities in a collaborative environment. Learners with a low level of action skills perform no or very little activity, while learners with a high level of action skills actively participate in familiar or unfamiliar contexts.

Interaction refers to learners' behaviors, contributions, and reciprocity during a collaborative activity. Learners with a low level of interactive skills are only receptive to communication and do not contribute to or participate in the communication, while learners with a high level of interaction skills respond to the communication and coordinate with other collaborators.

Task completion refers to learners' participation and perseverance when conducting a task or part of a task individually. Learners with a low level of task completion skills maintain presence only during the CPS process, while learners with a high level of task completion skill persevere in problem-solving by attempting different strategies.

Perspective Taking refers to the ability to understand others' contributions from a different perspective. This comprises two elements: adaptive responsiveness and audience awareness (mutual modeling).

Adaptive responsiveness refers to the ways in which learners ignore or accept others' contributions in a collaborative activity. Learners with a low level of adaptive responsiveness skill tend to ignore others' contributions, while learners with a high level of adaptive responsiveness skill integrate others' contributions into their thoughts; for instance, reconsidering the problem after accepting others' suggestions or using the contributions to suggest possible solutions.

Audience awareness refers to adaptability in one's behaviors or contributions to suit the others in the group. Learners with a low level of audience awareness skill rarely adapt or modify their contributions, while learners with high level of audience awareness skills modify their contributions to meet the group's needs; for instance, modifying their speed or utterances according to others' responses, or to making their interpretations easier to understand by considering others' perspectives.

Social Regulation refers to the strategies learners use to regulate their collaborative activities based on the identification of group diversity. In social regulation, four elements are involved: negotiation, self-evaluation (metamemory), transactive memory, and responsibility initiative.

Negotiation refers to the actions to reach a compromise when confronting conflicts within the group. Learners with a low level of negotiation skills merely comment on the differences. In contrast, learners with a high level of negotiation skills attempt to reach a common understanding and achieve compromise about the difference.

Self-evaluation refers to the ability to recognize one's strengths and weaknesses, and transactive memory refers to the ability to recognize others' strengths and weaknesses. Learners with a low level of self-evaluation/transactive memory skills note their own/others' performance only. In contrast, learners with a high level of self-evaluation/transactive memory skill infer their related capability based on their own/others' performance.

Responsibility initiative refers to the responsibility that a learner assumes for the progress of the group. Learners with a low level of responsibility initiative skill tend to solve the problem largely independently of others, while learners with high level of responsibility initiative skill conduct the task by connecting others; for instance, reporting to others when a task is completed and assuming group responsibility by using the first plural.

Cognitive skills comprise *Task Regulation* and *Learning and Knowledge Building*.

Task Regulation refers to the strategies learners use to regulate the task, in which planning is the core activity. *Task regulation* contains six elements: problem analysis, sets goals, resource management, flexibility and ambiguity, collects elements of information, and systematicity.

Problem analysis refers to the ability to analyze a problem and describe it in a familiar language. Learners with a low level of problem analysis skill just state a problem as presented, while learners with a high level of problem analysis skill device a problem into several subtasks and identify the necessary sequence of these subtasks.

Sets goals refers to the ability to set a clear goal for the problem. Learners with a low level of this skill only set the general goal for the problem as presented. In contrast, learners with high level of this skill set specific goals for each subtask and identify the relationships between subtasks.

Resource management refers to the ability to manage the available resource or divide labor to complete the task. Learners with a low level of resource management skill use resources without discussion with others, while learners with high levels of resource management skill provide suggestions about the use of resources or allocation of people to a specific task.

Flexibility and ambiguity refer to the ability to accept ambiguous situations. Many problems are ambiguous, especially in open-ended problem situations. Since open-ended problems permit multiple possible solution pathways, they are optimal for CPS (Chan & Clarke, 2017). Learners are expected to have the flexibility to face ambiguity. Learners with a low level of flexibility and ambiguity skills do nothing when facing ambiguous situations, while learners with a high level of flexibility and ambiguity skill note ambiguity, suggest the options, and explore the options further, such as change their plans in a flexible way.

Collects elements of information refers to the ability to explore and understand what information is necessary and how and when to acquire them. Learners with a low level of this skill identify the types of information and the required information for the current activity only, while learners with a high level of this skill understand the nature of information and identify the necessary information in the current, alternative, and future activity.

Systematicity refers to the level of the strategies used to gain solutions and monitor progress. Learners with a low level of systematicity skill conduct problem solving as a trial and error process, while learners with high level of systematicity skill use several strategies, techniques, and analysis to explore possible solutions, and conduct reflective monitoring activities.

Learning and knowledge building refers to the ability to understand and identify the relationships, cause and effect of the knowledge, and develop hypotheses. In *learning and knowledge building*, three elements are contained: Relationships (Represents and formulates), Rules: "If…then," and hypothesis "what if…," (Reflects and monitors).

Relationships refers to the ability to identify relationships between and among elements of knowledge. Learners with a low level of this skill tend to focus on the pieces of information separately, while learners with a high level of this skill link these elements and formulate patterns of the information.

Rules: "if…then" refers to the ability to set a plan based on the understanding of cause and effect of knowledge. Learners with low level of rules: "If…then" skills lack the understanding of consequences of actions, while learners with a high level of this skill set a plan, execute a sequence of actions, or decide a strategy based on the understanding of cause and effect.

Hypothesis "what if…" refers to the ability to set and test hypotheses, using a "what if…?" approach. Learners with a low level of hypothesis "what if…" skill do not modify their approach even if the information or circumstance changes, while learners with a high level of this skill explore additional options and search for new solutions based on the understanding of the problem.

1.1.3 Contexts of collaborative problem solving

In the session 1.1.3, I reviewed the contexts of CPS based on the framework of PISA 2015 (OECD, 2017). In addition to the core skills, student background is considered an important factor for CPS. In student background, the first factor is prior knowledge, which includes students' prior knowledge of mathematics, reading and writing, science, and society. The second factor in student background is characteristics, which includes students' attitudes, experience and knowledge, motivation, and cognitive ability.

Based on the above factors, PISA 2015 proposes the contexts of CPS: problem scenario, team composition, task characteristics, and medium. Problem scenario focuses on the type of the task (e.g., Jigsaw, negotiation), setting (e.g., formal or informal, using technology or not), domain content (e.g., mathematics, science, reading). Team composition includes the size of the group, the status, or the roles of the team members. Task characteristics include the openness of the task (e.g., well-defined or ill-defined), the information provided to learners, the interdependency for learners to solve the problem, and the goal setting. Medium includes semantic richness, referentiality to the real world, and the problem space. According to the contexts of CPS, when learners participate in CPS activities, the tasks should be designed based on a specific content, considering the connections between tasks with the real world.

In this study, I considered science as the main domain content and aimed to design lessons to improve students' CPS skills and learning performance. Since it is important to consider students' domain knowledge and their everyday learning and help them connect their knowledge with real situations, the knowledge and skills of multiple fields (science, technology, engineering, and mathematics) were integrated into lessons. Effective factors were also explored when designing CPS lessons.

1.2 Collaborative problem solving based STEM education

1.2.1 Definition and purpose of STEM education

In recent times, science, technology, engineering, and mathematics (STEM) education has been gaining attention worldwide. We currently face many global issues, including climate change, resource management, health, and biodiversity, that puts great pressure on institutions involved in developing science and technology; this requires continuous development of STEM education (Gough, 2015; Thomas & Watters, 2015). Considering the complexity and diversity of these issues and the need for the ability to integrate knowledge and skills in STEM fields to solve real problems and prepare for future life (Newhouse, 2016), science learning seems to be a powerful way of thinking and understanding the basis of these issues (Thomas & Watters, 2015).

According to National Science Foundation (2010), science includes core science subjects (such as physics and chemistry) and humanities and social sciences (such as politics and economics). In the STEM field, the aim is to use the knowledge and skills in natural science (core science) to consider the connections with society and the environment, solve global issues, and understand and contribute to the world. In addition to acquiring knowledge and skills in specific fields of STEM, it is possible for graduates specializing in STEM to work in other fields and transfer STEM knowledge and skills by integrating and using knowledge and skills in various fields (Siekmann, 2016).

STEM education incorporates multidisciplinary teaching and learning activities, including scientific inquiry, technology literacy, engineering design, and mathematics thinking (Kelley & Knowles, 2016).

Scientific inquiry includes learning activities to solve problems by acquiring scientific knowledge and skills, asking questions, setting hypotheses, and conducting investigations (Kelley & Knowles, 2016; Kennedy & Odell, 2014). Engineering design is generally used to connect the other three STEM domains to solve problems, including applying scientific knowledge and skills and mathematical analysis with the support of technology (Kennedy & Odell, 2014; Purzer, Goldstein, Adams, Xie, & Nourian, 2015). When using technology to support STEM education, it is important to integrate technology into the curriculum (Kennedy & Odell, 2014), which means viewing technology not only as a tool or artifact but also as learning processes regarding the method of designing or using the technology (Kelley & Knowles, 2016). Mathematical thinking includes mathematical knowledge and skills to solve problems, or mathematical analysis and reasoning to evaluate engineering design (Kelley & Knowles, 2016). Specifically, students are required to apply their scientific and mathematical knowledge and skills to find solutions for problems, especially in authentic situations, by utilizing technology and design in engineering practice (Holmlund et al., 2018; Kennedy & Odell, 2014).

According to Kelley and Knowles (2016), the foundation of the STEM learning framework is situated STEM learning, based on the situated cognition theory. Situated cognition theory emphasizes that learners' knowledge is constructed by authentic activities and contexts (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991). The ways in which existing knowledge and skill can be applied into the authentic contexts are important (Kelley & Knowles, 2016). Therefore, as a critical theme of STEM, acquiring knowledge and skills through solving problems with real-world scenarios is crucial in STEM education, as it helps students to prepare for real life and solve real-world problems by using science, technology, engineering, and mathematics-related knowledge and skills (Holmlund et al., 2018).

Moreover, situated cognition theory recognizes that not only the cognitive dimension but also the social dimension of learning activities is critical to the learning process. Rather than constructing knowledge by oneself, people's knowledge is constructed through socially communicating and interchanging with others (Lave & Wenger, 1991). In situated STEM learning, knowledge is organized around ideas, concepts, or themes, and evolved through social discourse. Thus, as one of the key elements of situated learning, a community of practice is considered the rope of all STEM domains, which connects science inquiry, technological literacy, mathematical thinking, and engineering design (Kelley & Knowles, 2016). The presence of knowledge and skills, the process of acquiring them through authentic contexts and the exchange of ideas, and ways to use them to solve authentic problems, including cognitive and social dimensions, should be considered in STEM education.

STEM education comprises three important elements: the integration of the STEM disciplines, instructional practices based on the STEM approach, and solving authentic situations by problem-solving skills (Herro et al., 2019; Holmlund et al., 2018; Wang, Moore, Roehrig, & Park, 2011).

First, multiple content areas and ideas in four STEM disciplines should be connected and integrated through a problem-based unit since the problem-solving process is critical to integrate STEM disciplines (Wang et al., 2011). In classrooms with a high level of field integration, the strengths of four disciplines were selected by using specialized knowledge, concepts, and theories, multiple sources of information.

The second element is that teachers structure the classroom environment and conduct instructional practices to facilitate problem solving. STEM education includes STEM instruction and STEM learning. STEM instructional practices include multiple STEM approaches such as problem-based approach, student choice, open-ended tasks, and technological support (Herro et al., 2019; Holmlund et al., 2018). In STEM classes, problems and tasks are placed in authentic situations and require students to solve these problems using multiple knowledge and skills. Therefore, ill-defined tasks and well-defined outcomes are two critical elements in STEM classes (Holmlund et al., 2018; Lee, Capraro & Bicer, 2019). The ill-defined task is under-described, through which students can use various strategies and approaches and develop content knowledge in the learning processes.

Moreover, to help students conduct effective STEM learning, the well-defined outcome should be considered, including a clear goal for the final product or solution for the task, consideration about the constraints during the learning processes, and specific assessment for students' learning as both a group and individual (Lee et al., 2019). Therefore, when conducting STEM learning, students can develop both conceptual and procedural understanding through learning processes. Students are encouraged to involve in choosing the topics, the design of the problems, the method of study, or even the assessment of the results. Appropriate technology is integrated in instructional design to support the problem-solving process by searching for information, creating products, or conducting mathematical analysis. In the STEM instructional practices, students learn STEM-related knowledge and skills by solving life- and work-related problems (Holmlund et al., 2018).

The last element is solving authentic situations by using problem-solving skills. Authentic situations include placing the problems and tasks in a real event, encouraging students to consider the relevant contents, and reflecting on the local implications (Wang et al., 2011). In STEM education, situated learning is considered as the foundation of the integration of four domains (Kelley & Knowles, 2016). Therefore, students can build a rich understanding of what they are learning by actively applying knowledge and skills to the authentic situation, rather than just acquiring them (Brown et al., 1989). Authentic activities are helpful for students to act meaningfully and purposefully since by conducting authentic activities, students are provided with experience to represent and describe the knowledge or concepts and revise their understanding and actions based on the experience and results (Brown et al., 1989). Based on situated STEM learning, engineering design approach enables students to build connections among STEM domains and apply scientific knowledge and inquiry in an authentic context. Students can construct new knowledge and enhance their learning through engineering practice and scientific inquiry (Kelley & Knowles, 2016). Students treat technology and engineering as cognitive tools, apply mathematical and scientific approaches to solve problems, generalize key concepts, and accumulate procedural knowledge (Lou, Liu, Shih, & Tseng, 2011). Thus, students are expected to develop and use their integrated knowledge and cognitive skills, such as problem-solving skills, through authentic contexts.

1.2.2 Collaborative problem solving based STEM education

STEM education is conceptualized as a multidisciplinary approach based on which instructors prepare problems for students to solve (Herro et al., 2019). As one of the success factors in STEM education, it is important to embed knowledge and skills in the curriculum and assess knowledge and skills in real-life situations or problem-solving practice processes and focus on the link of knowledge between the four STEM domains (Newhouse, 2016). STEM education allows students to examine and apply theories and knowledge to improve their problem-solving skills, and integrate the comprehension and application of complicated knowledge in STEM areas (Lou et al., 2011).

Problems in the real situation are complex and ill-defined and require students to share knowledge and ideas, discuss with others to reach an agreement, and search for and analyze relevant information (Lou et al., 2011; Savery, 2006). Therefore, in STEM education, students can benefit more from solving problems collaboratively than doing so individually (Hogan, 1999). As the goal of problem solving by collaboration in STEM education, students are expected to understand the facts and principles of the problem, identify and analyze the elements of the problem, examine the hypotheses they set, and finally reach the agreement on the solution they propose.

According to the OECD (2017), the contexts the CPS emphasized the problem scenario of a domain content, while considering the integration of the knowledge and skills in other domains as well. Therefore, it is effective to improve students' CPS skills in the content of the integrated STEM education. Mutually, CPS is also a promising area in STEM education because of its advantages in inculcating the understanding of scientific knowledge and others' ideas, training in scientific investigation, and solving applied problems (Hesse et al., 2015; Hogan, 1999; Lin, Yu, Hsiao, Chu, Chang, & Chien, 2015).

When students face certain situations involving solving complex problems, decision-making, and create new ideas for solutions, they are expected to collaboratively perform cognitive processes, which require skills associated with CPS (Andrews-Todd & Forsyth, 2020). Therefore, CPS shows great potential in solving complex problems in real situations (Hesse et al., 2015), one of the key points of effective STEM education (Holmlund et al., 2018; Kelley & Knowles, 2016).

In several existing studies, the CPS learning approach has proven beneficial to students' learning performance in STEM-related subjects, based on instructors' scaffolding and intervention (Lin et al., 2020; Raes et al., 2012). It is effective to incorporate the CPS learning approach into STEM education, such as integrating cognitive and social dimensions (Gu et al., 2015) or following the CPS processes proposed by Hesse et al. (2015). For example, CPS approaches were designed based on STEM contents in order to develop CPS skills, such as using semantic diagrams (e.g., Cai, Lin, & Gu, 2016) or teachers' intervention (e.g., Gu et al., 2015) as cognitive tools, or using a web-based system to support the execution and assessment of CPS activities (e.g., Lin et al., 2020). These studies indicated the effectiveness of integrating the CPS approach into the STEM contents, which also revealed the importance of clarifying the factors of CPS-based STEM instructional design.

The primary aim of CPS-based STEM education is to improve students' CPS skills and learning performance through integrated STEM learning (Cai et al., 2016). Based on previous studies, it is important to consider all sub-factors in CPS (Care et al., 2016; Hesse et al., 2015), and the important factors of STEM education (Herro et al., 2019; Holmlund et al., 2018; Wang et al., 2011). Considering the common points in contexts of CPS and STEM education, the following factors should be considered and integrated into the CPS-based STEM education in addition to the sub-factors in CPS.

First, the problem scenario should be set in specific domain content and integrated with the knowledge and skills in other domains.

Second, the tasks for students should be designed in authentic situations or real events. This encourages students to identify the contents relevant to them and consider the implications and significance with respect to their real lives (Wang et al., 2011).

Third, the CPS-based STEM education should be conducted based on STEM instructional practices, including ill-defined tasks and well-defined outcomes (Herro et al., 2019; Lee et al., 2019). When designing tasks during CPS-based STEM education, the characteristics of the tasks should be considered, including the openness of the tasks, the amount of necessary information and ways to convey those to students, the goal of the tasks and subtasks, and the utilization and the support of technology.

1.2.3 Challenges of collaborative problem solving based STEM education

STEM education in K-12 has received increasing attention worldwide and has been studied extensively. However, several challenges—such as the difficulty in integrating four STEM fields—still persist. In STEM education, the focus is generally placed on mathematics or science with little consideration of technology and engineering (Portz, 2015). Although many teachers can recognize the connections among science, mathematics, and engineering, and connect these three disciplines, it is difficult for them to integrate technology into instructional practices (Wang et al., 2011). According to Wang et al., teachers pointed out the existence of limited opportunities for students to engage with technology due to the limited technology resources in schools or the lack of training for teachers to design a good STEM curriculum.

The lack of guidance for STEM curriculum design is a challenge yet to be addressed (Herro et al., 2019). Several studies question whether STEM teachers have sufficient knowledge and skills relevant to the STEM disciplines (e.g., Portz, 2015). STEM teachers' lack of knowledge and skills will lead to difficulty in deciding the factors to be considered in the STEM curriculum design, such as teaching pace or time, the learning contents and processes designed to improve students' understanding (Wang et al., 2011). When learning STEM, students do not always have the opportunity to solve authentic problems in the classroom environment. Thus, it is important to design effective tasks, for example, open-ended problems (Bartholomew & Strimel, 2018; Chan & Clarke, 2017). Chan and Clarke (2015) found that the development of both collaborative and problem-solving skill sets was influenced by open-ended problems. In integrated STEM, solving open-ended problems based on engineering design was an effective method for learning since students perceived these problems as fun, engaging, creative, and less dependent on students' prior experiences with engineering design or group work than other problem scenarios (Bartholomew & Strimel, 2018; Guzey, Moore, Harwell, & Moreno, 2016). Considering the integration of the four STEM fields, it is necessary to clarify the kind of learning strategies used by students during STEM learning.

In addition, creating appropriate formative or alternative assessments for students' learning, especially for their work in groups, remains a challenge (Wang et al., 2011). When assessing students' work in STEM learning, teachers always use tests to assess students' knowledge and summaries or reports to monitor students' learning progress. Although it is necessary to assess students' STEM learning processes in order to improve the instructional design (Sergis, Sampson, Rodríguez-Triana, Gillet, Pelliccione, & de Jon, 2019), it is difficult for teachers to monitor the entire learning process by using traditional assessments such as test or observation. Although teachers can assess students' learning performance or knowledge acquisition from the results of tests or reports, it is difficult to understand students' learning behaviors, which represent students' actual participation.

Several challenges remain with regard to CPS-based STEM education, which integrates important factors of CPS in the context of STEM. Due to the complex and coordinated nature of CPS, it is important to identify the factors that might influence all the sub-skills of CPS and their development process. Although it is important to understand students' learning behaviors during the CPS learning processes in the context of STEM, it can also be challenging.

Moreover, it is difficult to integrate all factors regarding CPS and STEM education into one curriculum. Therefore, it is necessary to understand students' learning process and strategies, clarify the factors that might influence the CPS awareness, and improve the learning performance. It is necessary to provide some guidance for CPS-based STEM curriculum design, including the important factors that should be considered in the design. In previous studies, many instructional designs of CPS-based STEM education focused on the cognitive performance and human-computer or students' discussion during CPS learning (e.g., Andrews-Todd & Forsyth, 2020; Gu et al., 2015). Few studies consider the behavioral aspects during CPS-based STEM education and provide practicable guidance for instructional design.

1.3 Learning Analytics

1.3.1 Definition of learning analytics

Considering the integrative and complex nature of CPS and STEM education, it is important to clarify the learning process regarding how students engage in individual and collaborative learning and understand students' individual thinking behaviors and relate these learning behaviors with their learning strategy use.

Learning behaviors are important indicators of students' learning performance (Hwang, Shadiev, Wang, & Huang, 2012; Lowes, Lin, & Kinghorn, 2015) and individual learning awareness of instructional practice (Artino Jr. & Jones II, 2012; Yamada, Shimada, Okubo, Oi, Kojima, & Ogata, 2017). Since STEM learning allows students to combine theory and practice in real situations, it is necessary to explore the dimensions of cognition and behaviors in STEM, including how students comprehend and apply integrated knowledge (Liu & Cavanaugh, 2011). Thus, learning behaviors should be considered as critical factors that could affect the improvement of learning performance and CPS awareness.

Since it is not easy to capture students' learning behaviors during whole lessons, instructional experiments that focus on learning behaviors have mostly targeted online courses in higher education or long-term courses in secondary education. However, not all instructors in secondary education will adopt online instructions in the classes due to time constraints, limitations of equipment, and other issues.

Therefore, considering the difficulty in collecting behavioral data in a traditional face-to-face learning environment, learning analytics (LA) is an effective way to use online educational data to understand and improve the learning environment in various fields.

LA includes "the measurement, collection, analysis, and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning and the environments in which it occurs" (LAK, 2011). For example, students' learning logs through learning management systems (LMS) were collected to represent students' learning behaviors such as online participation during online learning (Morris, Finnegan, & Wu, 2005; Wang and Newlin, 2000), or through specific e-book readers to represent learning behaviors regarding reading digital learning materials (Ogata et al., 2017).

1.3.2 Role of learning analytics in collaborative problem solving-based STEM education

Dunbar, Dingel, & Prat-Resina (2014) indicated the importance of incorporating the educational data and analysis relevant to student learning into the course and curriculum design. They also pointed out the need for methods that researchers and teachers can use to explore data on instructional practices. Although LA is an effective method to assess the ways in which online behaviors are associated with learning performance in secondary education (Lowes et al., 2015), there are still fewer studies using LA data at the secondary education level than higher education. Liu and Cavanaugh (2011) collected learning logs for one academic year in biology courses in high school to show that certain variables could affect student academic achievement. For example, the time students spent in the LMS positively and significantly affected their final scores in biology courses. Lowes et al. (2015) also explored LMS data for one academic year to examine the link between in-course behaviors and course outcomes, concluding that the level of online behaviors associated with attendance and interactivity showed a positive influence on final grades. However, it is difficult to conduct continuous online courses in secondary education due to time restrictions and limited availability of equipment, among other issues.

To support teachers in design learning, Hernández-Leo, Martinez-Maldonado, Pardo, Muñoz-Cristóbal, & Rodríguez-Triana (2019) proposed a framework of analytics layers for learning design to identify different functions based on multiple analytics methods. In this framework, three layers were included: learning analytics, design analytics, and community analytics. The learning analytics layer was related to data sources of students' profiles, learning behaviors and processes, and learning performance in a learning environment.

However, it is difficult to contextualize some of the findings only generated from LA data since the data are incomplete regarding the curriculum design or teachers' teaching behaviors with the curriculum (Monroy, Rangel, & Whitaker, 2014). According to Monroy et al. (2014), concerning K-12 curriculum design, it was necessary to incorporate LA data along with traditional measures, such as questionnaires and classroom observation, to help to contextualize the findings generated from LA data. Therefore, in this study, an LA approach was used to collect students' learning logs during their CPS-based STEM learning to represent their learning behaviors concerning digital learning materials and used traditional questionnaire measurement to measure their learning awareness about CPS and STEM learning strategies.

1.4 Research Purpose

In most of the existing studies, CPS processes were designed and integrated into STEM education regarding cognitive and metacognitive strategies. However, few studies considered the ways to design CPS processes regarding the behavioral dimension. Therefore, this study aims to improve students' CPS skills and learning performance, by identifying effective behavioral factors combined with psychological data and integrating these factors into CPS processes in the context of STEM education.

I used an LA approach to collect students' learning logs, represented their learning behaviors concerning individual thinking during CPS-based STEM learning, and connected them with learning strategies. This study aims to clarify the relationships among CPS learning awareness, learning strategy, learning behaviors, and learning performance; discern the factors that might improve learning performance and CPS skills, and provide guidance on ways to integrate these factors into CPS-based STEM education.

1.5 Structure and Hypotheses of this Dissertation

1.5.1 Structure of this Dissertation

The study was conducted according to the following procedure:

Chapter 1 (this chapter) describes the definition and background of STEM education, CPS-based STEM education, the background, role, and challenges of the LA approach for designing CPS-based STEM education. Based on these backgrounds, the aim of this study is clarified, and hypotheses and research questions based on the aim are presented.

Chapter 2 reviews the literature on the theory of STEM education and CPS and a global view of the design of CPS-based STEM education. Then, effective use of LA approach, especially the integrative use of qualitative and quantitative analysis is reviewed, to obtain important factors and effective methods regarding the design of CPS-based STEM education.

Chapter 3 presents the design, implementation, and results of four instructional practices, to identify the important factors of the CPS process in science education regarding CPS awareness, motivation, and learning behaviors.

Chapter 4 presents the design, implementation, and results of one instructional practice, which is designed based on the integration of STEM fields. Important factors of the CPS process in the context of STEM education regarding CPS awareness, STEM learning strategies use, and learning behaviors, and the features of individual learning and group work are identified.

Chapter 5 presents the design, implementation, and results of one instructional practice, which is designed based on the results of the former instructional practices. Important factors of the CPS process in STEM education regarding CPS awareness and skills, STEM learning strategies use, and learning behaviors are examined. The features of different learning phases, individual learning and group work, and the learners' prior knowledge influence are identified. Based on the results, an effectiveness design for CPS-based STEM education is proposed.

Finally, Chapter 6 summarizes our research findings, provides some implications, and presents limitations and future work of the research.

1.5.2 Hypotheses of this Dissertation

The main aim of this study is to design STEM lessons to improve students' CPS skills in STEM content. It emphasizes the important factors affecting CPS improvement and learning performance (considered as learning effectiveness of CPS-based STEM lessons) and clarifies the reason for, and manners in which these factors affect the learning effectiveness in different learning situations.

Based on existing studies, the following hypotheses were proposed.

In STEM content, the problems are focused on the authentic situations, in which the problems are usually complex and ill-defined (Lou et al., 2011). Students construct knowledge and understanding of related contents by solving the ill-defined problems by individual efforts and group contributions (Hogan, 1999). As one of the goals of STEM education, students are expected to acquire knowledge during the activities of solving problems with authentic contexts or apply them to authentic problems (Holmlund et al., 2018). Therefore, it is assumed that students' learning performance regarding the understanding and application of scientific knowledge is improved through the CPS activities in the contents of STEM (H1).

H1. The learning performance is improved after the CPS-based STEM lessons.

In CPS-based STEM lessons, the CPS process framework (Hesse et al., 2015), including collaboration and problem solving dimensions, was integrated into the design. The CPS process framework contains instructions on how to conduct CPS activities by using specific sub-skills of CPS. Therefore, it is assumed that students' CPS awareness, including each sub-factor, is improved through the CPS activities in the contents of STEM (H2).

H2. All sub-factors CPS awareness is improved after the CPS-based STEM lessons.

In order to identify what factors have effects on the learning effectiveness, including learning performance and CPS awareness, it is important to examine the relationships between learning performance and CPS awareness with the factors related to the instructional design and students' learning activities.

H3. The learning effectiveness of CPS-based STEM lessons (learning performance and CPS awareness) is related to psychological, behavioral, and strategic factors.

According to the framework of PISA 2015, in CPS, in addition to the core skills, collaborative skills, and problem-solving skills, it is necessary to consider students' background, including their attitudes, experience and knowledge, and motivation into the design (OECD, 2017). Motivation is an essential factor related to learners' effort and autonomy to regulate their learning (Schunk, 1991; Zimmerman and Schunk, 2008). Students choose different learning strategies based on their different motivational levels such as interests, mastery, causal attributions, enjoyment. This leads to difference in achieving their learning outcomes (Schumacher and Ifenthaler, 2018; Zimmerman and Schunk, 2008; Sakurai and Takano, 1985). Therefore, it is assumed that students' motivation can help students achieve the learning goals and improve learning performance and their CPS awareness.

H3-1. The learning effectiveness of CPS-based STEM lessons is related to learning motivation.

In STEM learning, understanding students' learning processes is helpful when teachers need to provide students with appropriate, customized guidance (Sergis, Sampson, Rodríguez-Triana, Gillet, Pelliccione, & de Jong, 2019). In addition, in CPS learning, which includes cognitive and collaborative dimensions, students conduct cognitive processes during both individual learning and collaborative activities. Students' cognitive learning behaviors were related to their choice of learning strategies (Sun, Lin, & Chou, 2018) and influenced learning performance. For example, De Barba, Kennedy, & Ainley (2016) used behavior variables, including access to the learning material videos and quizzes, to predict the learning performance for online courses. Therefore, in CPS learning, the learning behaviors regarding students' cognitive processes are related to the choice of specific strategies and affect learning performance. Moreover, since the cognitive process is a part of CPS processes, cognitive learning behaviors affect the CPS learning or be affected by students' level of CPS skills. Therefore, it is assumed that students' learning behaviors are related to their learning outcomes, including learning performance and CPS awareness.

H3-2. The learning effectiveness of CPS-based STEM lessons is related to learning behaviors.

As indicated above, the student's motivation and learning behaviors were related to learning strategies. Chan and Clarke (2017) found that open-ended problems influenced developing both collaborative and problem-solving skill sets. In integrated STEM, solving open-ended problems based on engineering design was an effective method to learning STEM since students perceived that this kind of problem was more fun, engaging, creative, and less dependent on students' prior experiences with engineering design than other problem scenarios (Bartholomew & Strimel, 2018; Guzey et al., 2016). Considering the integration of the four STEM fields, the kinds of learning strategies students were using were effective to CPS-based STEM learning.

H3-3. The learning effectiveness of CPS-based STEM lessons is related to learning strategies.

According to PISA 2015 (OECD, 2017), the contexts of CPS, such as problem scenario and team composition, should be considered. Problem scenario focuses on the type of the task (e.g., Jigsaw, negotiation), setting (e.g., formal or informal, using technology or not), domain content (e.g., mathematics, science, reading). Team composition includes the size of the group, the status, or the roles of the team members. Therefore, it is indicated that when students participate in CPS activities, the learning effectiveness is related to the setting of learning activities, including individual learning and group work. Hence, the different types of learning activities, including individual learning and group work, affect learning effectiveness, have effects on learning performance and CPS awareness.

H4. In individual learning and group work, the learning effectiveness of CPS-based STEM lessons are different.

According to PISA 2015 (OECD, 2017), in CPS, student background is considered as an important factor for CPS. In student background, one important factor is prior knowledge, including students' prior knowledge of mathematics, reading and writing, science, and society. Since students might have different prior knowledge about the related topics and this prior knowledge would have an influence on the acquisition of new knowledge and final outcomes (Dinsmore, Baggetta, Doyle, & Loughlin, 2014), it is assumed that the level of prior knowledge has effects on the learning effectiveness including learning performance and CPS awareness.

H5. The level of prior knowledge affects the learning effectiveness of CPS-based STEM lessons.

Finally, since the learning activities in all the instructional practices were designed based on the CPS processes in STEM contexts, students' CPS skills improved after the CPS-based STEM lessons.

H6. The CPS skills are improved after the CPS-based STEM lessons.

Based on the above hypotheses, the research questions in each chapter in this dissertation were summarized in **Table 2**.

Table 2 The research questions (RQs) related to hypotheses in this dissertation

<table>
<tr><th colspan="2">Hypothesis</th><th>RQ</th><th>Data collection</th><th>Data analysis</th></tr>
<tr><td colspan="2" rowspan="2">H1. The learning performance is improved after the CPS-based STEM lessons</td><td>RQ2-a, RQ3-a, RQ4-a, RQ5-a</td><td rowspan="2">• Performance test</td><td>Wilcoxon Signed-rank Test</td></tr>
<tr><td>RQ6-a</td><td>Paired sample t-test</td></tr>
<tr><td colspan="2" rowspan="2">H2. All sub-factors CPS awareness is improved after the CPS-based STEM lessons</td><td>RQ1-a, RQ2-b, RQ3-b, RQ4-b, RQ5-b</td><td rowspan="2">• CPS questionnaire</td><td>Wilcoxon Signed-rank Test</td></tr>
<tr><td>RQ6-b</td><td>Paired sample t-test</td></tr>
<tr><td rowspan="3">H3. The learning effectiveness is related to psychological, behavioral, and strategic factors</td><td>H3-1. The learning effectiveness is related to learning motivation</td><td>RQ1-b, RQ2-c, RQ3-c, RQ4-c</td><td>• Performance test
• CPS questionnaire
• Motivation questionnaire
• Learning logs</td><td rowspan="2">Spearman Rank Correlation</td></tr>
<tr><td>H3-2. The learning effectiveness is related to learning behaviors</td><td>RQ3-c, RQ4-c, RQ5-c, RQ5-d, RQ5-e, RQ6-c, RQ6-d</td><td>• Performance test
• CPS questionnaire
• Learning logs</td></tr>
<tr><td>H3-3. The learning effectiveness of CPS-based STEM lessons is related to learning strategies</td><td>RQ5-c, RQ5-d, RQ5-e, RQ6-c, RQ6-d</td><td>• Performance test
• CPS questionnaire
• STEM learning strategy questionnaire
• Learning logs</td><td>• Spearman Rank Correlation
• Path analysis</td></tr>
<tr><td colspan="2">H4. The differences between individual learning and group work have effects on the</td><td>RQ5-c, RQ5-d, RQ5-e, RQ6-e</td><td>• Performance test
• CPS questionnaire
• STEM learning strategy</td><td>• Wilcoxon Signed-rank Test
• Spearman</td></tr>
</table>

learning effectiveness		questionnaire • Learning logs	Rank Correlation
H5. The level of prior knowledge affects the learning effectiveness	RQ4-d, RQ5-f, RQ6-f	• Performance test • CPS questionnaire • STEM learning strategy questionnaire • Learning logs	Multiple regression analysis
H6. The CPS skills are improved after the CPS-based STEM lessons	RQ4-e, RQ5-g, RQ6-g	Records of discussion	Dialogue analysis

The specific RQs in each chapter are presented as follows:

Chapter 3

Instructional practice 1

RQ1-a: Did each factor of CPS awareness change after the STEM lessons?

RQ1-b: What were the relationships between the changes in CPS awareness, learning performance, and learning motivation in STEM lessons?

Instructional practice 2

RQ2-a: Did the learning performance change after the STEM lessons?

RQ2-b: Did each factor of CPS awareness change after the STEM lessons?

RQ2-c: What were the relationships between the changes in learning performance, changes in CPS awareness, and learning motivation in STEM lessons?

Instructional practice 3

RQ3-a: Did the learning performance change after the STEM lessons?

RQ3-b: Did each factor of CPS awareness change after the STEM lessons?

RQ3-c: What were the relationships between the changes in learning performance, changes in CPS awareness, and learning motivation in STEM lessons?

Instructional practice 4

RQ4-a: Did the learning performance change after the STEM lessons?

RQ4-b: Did each factor of CPS awareness change after the STEM lessons?

RQ4-c: What were the relationships between the changes in learning performance, changes in CPS awareness, learning motivation, and learning behavior in STEM lessons?

RQ4-d: Between high and low learning performers, what was the difference in motivational and behavioral factors that influence learning performance and CPS awareness?
RQ4-e: How did students display CPS skills during the discussion?

Chapter 4
Instructional practice 5
RQ5-a: Did the learning performance change after the STEM lessons?
RQ5-b: Did each factor of CPS awareness change after the STEM lessons?
RQ5-c: Which factors of STEM learning strategy and learning behaviors had relationships with the change in learning performance?
RQ5-d: Which factors of STEM learning strategy and learning behaviors had relationships with the change in CPS awareness?
RQ5-e: What were the relationships between STEM learning strategy and learning behaviors?
RQ5-f: How did students display CPS skills during the discussion?

Chapter 5
Instructional practice 6
RQ6-a: Did the learning performance change after the STEM lessons?
RQ6-b: Did each factor of CPS awareness change after the STEM lessons?
RQ6-c: What were the effects of students' learning behaviors, changes in the use of STEM learning strategies, and changes in CPS awareness on improving learning performance?
RQ6-d: What were the effects of students' learning behaviors on the improvement of learning performance in different learning phases?
RQ6-e: What factors of learning behavior affected the improvement of learning performance and CPS awareness during in-class and out-of-class learning?
RQ6-f: What was the difference in strategic and behavioral factors that influence learning performance and CPS awareness between high and low learning performers?
RQ6-g: How did students display CPS skills during the discussion?

Chapter 2: Literature Review and Significance of the Research

2.1 Literature Review regarding CPS Learning Activities Design in STEM Education

As for the CPS design in STEM education, many previous studies focused on designing specific CPS activities or general instructions to improve students' CPS skills and learning performance.

First, concerning the design of CPS activities, Andrews-Todd & Forsyth (2020) used online simulation-based tasks, which should be conducted by peers, to explore and assess students' social and cognitive dimensions. However, each task contains one problem and is mainly related to one subject in science (such as chemistry, physics). Lin et al. (2015) developed a system for students to conduct simulation-based CPS tasks based on the human-computer interaction and measured students' CPS skills through this system.

2.2 Literature Review regarding CPS Instructional Design in STEM Education

As for the general instructional design for CPS courses in STEM education, first, concerning the social dimension, previous studies emphasized the assessment of collaboration activities rather than the instructional design. For example, Herro et al. (2019) developed a rubric, named Co-Measure, to assess student collaboration at the individual level during STEAM activities. In the cognitive dimension, previous studies focused more on instructional design. For example, Cai et al. (2016) used a semantic diagram as a cognitive tool to support students' CPS learning in a science lesson.

As for the studies that integrated two dimensions, Gu et al. (2015) designed an intervention framework combining social interaction of collaborative learning and cognitive support of problem solving to develop students' CPS skills. Lin et al. (2020) compared the effectiveness of the web-based CPS system and the classroom-based hands-on activities, including the CPS scenarios from daily life, in order to develop students' CPS skills in STEM learning. The virtual STEM learning environment was more effective in developing their CPS skills than traditional classroom-based hands-on activities, and the effectiveness of the system would be further enhanced with the teacher's involvement and guidance.

However, all these previous studies did not consider the behavioral dimension related to students' learning strategy during the learning process.

2.3 Literature Review regarding Learning Behaviors in Instructional Design

To improve students' STEM learning, it is necessary for teachers to understand students' learning processes and provide them with appropriate, customized guidance (Sergis et al., 2019). In this regard, the LA approach is considered to be effective in providing evidence of students' learning data regarding their learning processes and helping teachers in their instructional design, such as how to design appropriate activities for students (Dunbar et al., 2014; Hernández-Leo et al., 2019; Sergis et al. 2019).

Many previous studies showed that learning behaviors were related to the improvement of students' learning performance in secondary education (e.g., Lowes et al., 2015). For example, Lowes et al. (2015) conducted an online course in high school and confirmed the positive relationship between learning behaviors and learning performance. In order to examine related learning behaviors in CPS learning, Gu et al. (2015) conducted observations to understand students' learning process and specialize their CPS skills by analyzing the group discourse. Observation, such as collecting and analyzing discourse and video recordings, is a usual method when understanding learners' learning behaviors, actions, learning processes. However, it is difficult to understand students' usual learning situations by conducting qualitative analysis merely since this approach is labor-intensive and time-consuming, which limited the use in the unusual lessons for teachers and researchers.

In order to support teachers in design learning, Hernández-Leo et al. (2019) proposed a framework of analytics layers for learning design to identify different functions based on multiple analytics methods. In this framework, three layers were included: learning analytics, design analytics, and community analytics. The learning analytics layer was related to data sources of students' profiles, learning behaviors and processes, and learning performance in a learning environment. The learning analytics layer interacts with the design analytics layer of students' actions regarding tasks, and the community analytics layer is regarding actions in a community.

Many studies adopted the LA approach to understand students' learning behaviors in CPS learning, especially to understand their cognitive process. For example, Kwon et al. (2018) identified students' learning behavior patterns during their inquiry tasks and explored the relationship between the learning behaviors and students' domain knowledge. They indicated some meaningful inquiry behaviors that should be encouraged during problem-solving learning. As one example of a large-scale study by using the LA approach, Greiff, Wüstenberg & Avvisati (2015) conducted log-file analysis by capitalizing on the computer-based assessment of problem solving in PISA 2012 assessment to understand students' behavior when working on problem-solving items. Their results provided great potential for researchers and teachers, such as help researchers and teachers understand students' cognitive behaviors and identify the hidden patterns of behaviors and strategies.

According to Monroy et al. (2014), concerning K-12 curriculum design, it was necessary to incorporate LA data along with traditional measures, such as questionnaires and classroom observation, since these traditional measures could help to contextualize some of the findings generated from LA data. For example, Vujovic, Hernández-Leo, Tassani & Spikol (2020) examined the effects of physical environments in a classroom on students' learning behaviors in CPS learning. Their research used mixed methods, including qualitative analysis of video recordings of students' learning activities, and quantitative analysis of students' actions during CPS learning. The qualitative and quantitative results were analyzed and discussed to illustrate and expand the results indicated by the statistical analysis. This research provided some implications about the effective design of the physical environments in CPS learning.

As for the learning behaviors regarding students' cognitive processes, in Andrews-Todd & Forsyth's (2020) research, they conducted a qualitative analysis to assess students' online chat and used the LA approach to explore students' problem-solving process during online simulation-based tasks. Similarly, Chang et al. (2017) examined how students solved a physics problem using individual-based and collaborative simulations by conducting mixed methods. Multiple data sources were analyzed, including group discourse in the text chatroom, log data to represent problem-solving activities, learning test scores, and questionnaires. The results indicated that students using individual-based and collaborative simulations showed different behavior patterns.

However, these previous studies focused on the investigation of cognitive processes by the LA approach rather than the general learning activities and processes. Therefore, in our research, we used an LA approach to collect students' learning logs, represent their learning behaviors during their CPS-based STEM learning, and used traditional questionnaire measurements to measure their learning awareness about CPS and STEM learning strategies. The results of both qualitative and quantitative analysis were analyzed and discussed to clarify the effective learning behaviors and learning strategies on general or specific learning situations.

2.4 Significance of the Research

As presented in Figure 1, Andrews-Todd & Forsyth's (2020) designed online simulation-based tasks to explore and assess students' social and cognitive dimensions. They conducted a qualitative analysis to assess students' online chat and used the LA approach to explore students' problem-solving processes. However, the analysis in their research did not include the general learning activities during the CPS learning. Gu et al. (2015) designed a CPS intervention framework in science education and conducted observations to understand students' learning process. However, this approach was labor-intensive and time-consuming, which limited the use in the unusual lessons for teachers and researchers.

Therefore, our research was placed as the instructional design of CPS-based STEM education, based on the connection between qualitative analysis and learning behavior to understand students' learning process and the integration of behavioral dimension with learning performance and psychological dimension.

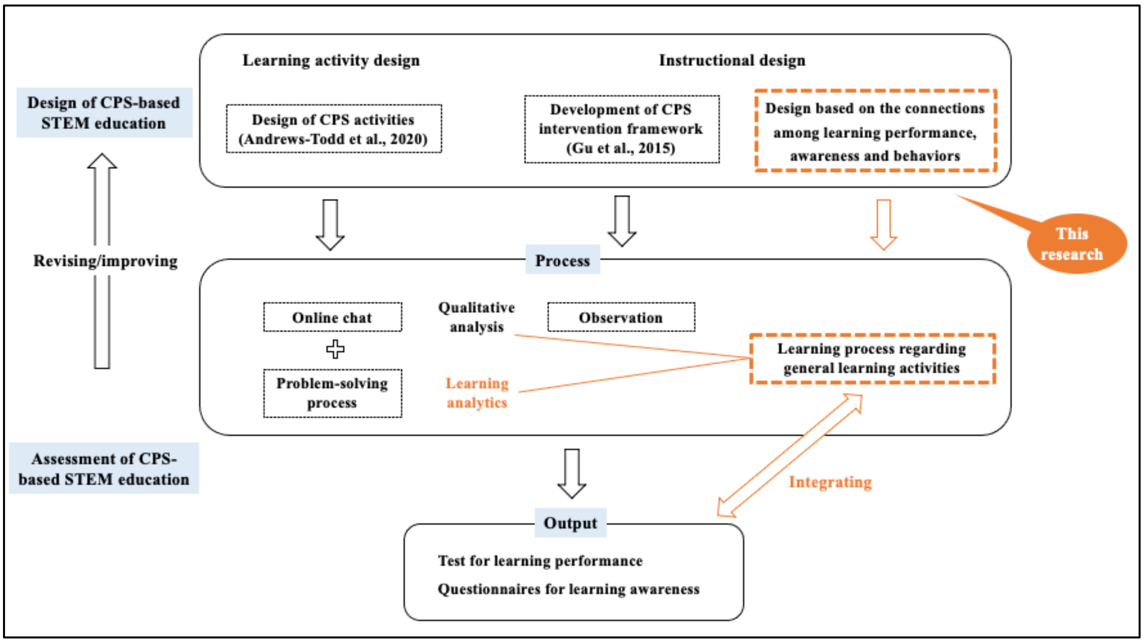


Figure 1. Significance of the Research

Chapter 3: Instructional practices for Identifying Factors of Effective Collaborative Problem Solving Process in Science Education

3.1 The aim of four instructional practices

Considering the integrative nature of CPS and STEM education, it is necessary to clarify what factors might influence the CPS awareness, and finally, to improve the learning performance so that these factors should be considered in the CPS-based STEM lessons. However, it is challenging to integrate all STEM disciplines, especially engineering and technology, into one STEM course. Therefore, in instructional practice1~4, the aim is to emphasize the science lesson design first and to clarify the factors that influence the CPS awareness and learning performance in science education.

3.2 Design overview of four instructional practices

Nowadays, some issues such as human health or environmental problems are receiving global attention. In order to solve these problems, the knowledge, skills, and findings of science are indispensable for solving these problems. In this chapter, four instructional practices were designed to arouse students' attention for authentic health, medical, and environmental problems and make them reflect on their own lives. These practices were designed in science lessons as the major domain context and were integrated with the knowledge and skills of other domains.

The aims of designing and assessing the four instructional practices include two dimensions, the effectiveness of CPS design and the outcomes of STEM lessons. First, regarding the CPS design, four instructional practices aimed to improve students' CPS skills, using individual thinking and collaborative skills to solve problems in different contexts. Second, concerning the outcomes of STEM lessons, four instructional practices aimed to acquire related knowledge and apply the knowledge to authentic problem-solving.

These four practices were conducted in twelfth-grade science classes in a public senior high school in Japan. Students were divided into small groups (three~four students per group) according to their seats or student numbers to minimize the heterogeneity of the group composition. Here, the situations of the experiment school are described regarding the following two dimensions, the STEM teaching and learning experience and the use of technology. First, students' usual science lessons are designed and conducted based on the textbooks and merely focus on one major subject. Teachers do not integrate other fields' knowledge and skills into science lessons and design well-defined problems for students more often than ill-defined problems. As for students' learning, most students have not experienced STEM learning, which is designed based on multiple fields, ill-defined problems, and well-defined outcomes. Second, the technology was not integrated into their usual teaching and learning in this experiment school. Thus, when the systems were used in the instructional practices in order to support students' cognitive and collaborative activities, guidance and practice time were provided to students.

3.3 Design and assessment of instructional practice 1

3.3.1 The design of instructional practice 1

In science education, problem-solving is a critical factor for students' learning. Therefore, in addition to basic scientific knowledge and facts, students should also develop skills including problem-solving, communication, and thinking skills (Carlgren, 2013).

In instructional practice 1, two elements of collaboration, which are understanding what other collaborators are doing, and understanding how other collaborators have done (Miyake and Shiramizu, 2003), three elements of problem-solving, which are tasks related to authentic situations, clarification of problem-solving goals, various solutions (Quigley, Herro, & Jamil, 2017), were integrated into the design.

According to Miyake and Shiramizu (2003), it is effective for students to collaborate with others since they can understand what other members are doing or thinking, as well as the strength or weaknesses of the methods other members are using. In this instructional practice, in order to help students understand what and how others were doing, students were required to share their information and ideas to the group and submit the solutions to the class through the system. In addition, regarding the division of labor of the group, students should discuss and decide who was in charge of each sub-problem. Since each sub-problem was related, student assigned to each problem needed to explain the solution for the problem and the process of how he/she solved the problem to other group members.

As for the cognitive dimension, when engaging in authentic learning activities involving open-ended problems concerning the real world, it is essential to consider students' inquiry skills, creativity, and critical thinking (Krajcik, McNeill, & Reiser, 2008). Therefore, three factors regarding the problem-solving process proposed by Quigley et al. (2017) were integrated into this instructional practice: (1) using problems related to the real world, (2) clarifying the purpose of problem-solving, and (3) various solutions for one problem.

In this practice, two dimensions, collaboration and problem-solving, were considered in the design, and the effectiveness of the CPS learning was examined. Moreover, the relationships between CPS awareness, learning performance, and learning motivation were examined to determine what factors would influence the improvement of CPS awareness.

Therefore, the following research question (RQ) were set:

RQ1-a: Did each factor of CPS awareness change after the science lessons?
RQ1-b: What were the relationships between the changes in CPS awareness, learning performance, and learning motivation in science lessons?

3.3.2 Context and procedure of instructional practice 1

The theme of this science lesson was *Immunity*. This lesson was designed for students to understand the mechanism of immunity that maintains the internal environment of living organisms based on an example of a familiar disease (common cold) and recognize the relationship between immunity and illness. The final goal of the problem was to identify the advantages and disadvantages of taking cold medicine and reach an agreement within the group based on explaining the specific reasons. The problems were designed to encourage students to reflect on their attitudes and appropriate measures for usual diseases based on scientific principles. Students learned scientific knowledge through inquiry process (science), they searched information on the Internet and used Moodle system (Figure 2) to share the information and the solutions to other students (technology), and students were required to develop a solution regarding the appropriate measures for the cold, as the final product for CPS learning (engineering). However, mathematics-related knowledge and skills were not designed in this practice.

In order to assess whether students achieved the goal of problem-solving by group, each group was required to make a presentation to answer the provided problems as the final product of CPS learning. The teacher assessed whether the agreement of the group was correct and provided feedback and comments on each group's presentation. In this practice, there could be more than one correct answer, which means that the answer is judged as correct whether the students choose to take cold medicine or not, as long as they state the reasonable reasons. The reasons include the advantages (for example, alleviating symptoms) and disadvantages (not killing viruses and curing a cold itself) of taking cold medicine.

The practice 1 was conducted in a twelfth-grade science class in one lesson (50 minutes), with the participation of 29 students. Before the lesson, students were required to answer the CPS Awareness Questionnaire (CPS Questionnaire), according to the reference of Hesse et al. (2015) as a pre-questionnaire. After the lesson, students were required to answer the same CPS Questionnaire and new Motivation Questionnaire, which was developed by Miyake and Shiramizu (1985) as post-questionnaires. The contents and items of the CPS Questionnaire and Motivation Questionnaire are presented in Appendix 1 and 2. After the whole lesson, a post-test was conducted to check students' acquisition of related knowledge.

Figure 2. The Interface of Moodle system used in instructional practice 1

3.3.3 Results of instructional practice 1

RQ1-a: Did each factor of CPS awareness change after the science lessons?

First, Wilcoxon Signed-rank Test was conducted to examine the changes in CPS awareness after the lesson. As the results indicated, students' *Participation* awareness in the social dimension and *Learning and Knowledge Building* awareness in the cognitive dimension were significantly improved. However, the other factors of CPS did not change after the lesson, which indicated that it was necessary to consider and improve the elements of collaboration and problem-solving and integrate these two elements to improve the integrated CPS awareness.

RQ1-b: What were the relationships between the changes in CPS awareness, learning performance, and learning motivation in science lessons?

The post-test was conducted to examine the acquisition of related knowledge after the lessons. In order to explore what factors were related to these two types of awareness, Spearman's Rank Correlation Coefficient was used to examine the relationships between CPS awareness, learning performance, and motivation factors. As the results indicated, *Participation* awareness was negatively related to *Internal Causality* in motivation, and *Task Regulation* awareness was positively related to *Enjoyment* in motivation. The results showed that students' internal motivation was related to social awareness, and the enjoyment mutually influenced cognitive awareness. Therefore, it is expected to incorporate these motivational factors that attract the students' interest into a future instructional design.

3.4 Design and assessment of instructional practice 2

3.4.1 The design of instructional practice 2

According to the results in instructional practice 1, the CPS awareness in the social dimension did not change, indicating the insufficiency of the design. In CPS learning, it is practical to integrate the collaboration process and problem-solving process (OECD, 2017). Therefore, it is essential to integrate the social dimension and cognitive dimension rather than considering the social dimension and cognitive dimension separately.

In instructional practice 2, the CPS process framework proposed by Hesse et al. (2015) was considered in the design. In this practice, all inquiry activities were designed following the CPS process framework, which integrates a set of collaborative processes and problem-solving processes. The CPS processes in this practice are described as following:

- *Identifying the problem*: Understand the problematic situation by analyzing initial and hidden information on the problem. Recognize the problem as the gap between current states and expected goals and inform other group members about this discrepancy.
- *Representing the problem*: Select and organize the information, and integrate it with prior knowledge by using graphs, tables, symbols, and words to represent the information through coordination and communication, so that individual representations can be similar among the group.
- *Planning and executing*: Clarify the problem goal and establish a shared plan and sub-goals to accomplish the goal by managing shared information and resources, so that each member can have the same knowledge and understanding. The group then executes the plan.
- *Monitoring and reflecting*: Evaluate the action, reformulate the plan if necessary, and decide how to proceed based on an awareness of the group's progress on the problem they face and resources available within the group, to ensure each member understands the state of the group.

In this practice, collaboration and problem-solving were integrated into the design, and the effectiveness of the CPS learning was examined. Moreover, the relationships between CPS awareness, learning performance, and learning motivation were examined to determine what factors would influence the improvement of learning performance and CPS awareness.

Therefore, the following research questions were set:

RQ2-a: Did the learning performance change after the science lessons?

RQ2-b: Did each factor of CPS awareness change after the science lessons?

RQ2-c: What were the relationships between the changes in learning performance, changes in CPS awareness, and learning motivation in science lessons?

3.4.2 Context and procedure of instructional practice 2

The theme of the science lesson was *Limnic Eruption*, which was based on a natural disaster that happened in 1986.

The description of the case: *Lake Nyos is a crater lake in Cameroon. In 1986, massive amounts of dissolved CO_2 suddenly erupted from the bottom of the lake and caused a limnic eruption. The eruption caused asphyxiation and the death of around 1700 people living nearby. There is still concern about recurring gas hazards.* Figure 3 presents the images of Lake Nyos before and after

the limnic eruption.

Figure 3. Lake Nyos before (left) and after (right) the limnic eruption
(http://niyas.xsrv.jp/attoexa/2011/11/lake_nyos/)

The theme was related to knowledge of chemistry and geography and had a great impact on the ecosystem. Students were asked to think of a series of questions to find out the mechanism of limnic eruption and clarify the relationship between the environment and human beings. The final goal of the problem was to propose a manual of disaster reduction based on the consensus within the group. The problems were designed to encourage students to reflect on their attitudes and appropriate measures for the unavoidable disaster. In this lesson, students learned scientific knowledge about carbon dioxide and the weather through inquiry process (science), they searched information on the Internet and used Moodle system to share the information and the solutions to other students (technology), and students were required to develop a solution regarding the appropriate measures when facing such natural disaster, as the final product for CPS learning (engineering). However, mathematics-related knowledge and skills were not designed in this practice.

Same as instructional practice 1, each group was required to make a presentation as the final product of CPS learning. The teacher assessed whether the agreement of the group was correct and provided feedback and comments on their presentation. In this practice, the presentation contents were the manual of disaster reduction created by each group. The solutions in the manual of disaster reduction could be various and be judged as correct as long as they state the correct mechanism of the disaster, the reasonable measurements for the disaster, and similar unavoidable natural disasters. The measurements include the actions to detect the concentration of carbon dioxide, understand how to reduce the concentration, the dangers of natural disaster, and how to protect themselves and other people when facing such unavoidable disasters such as the earthquake or mudslide.

The study was conducted in a twelfth-grade science class in two continuous lessons (100 minutes), with the participation of 36 students. Before the lesson, students accepted a pre-CPS Questionnaire and a pre-test to check their prior knowledge of the related knowledge. After the lesson, they accepted the CPS Questionnaire and Motivation Questionnaire as post-questionnaires and the same post-test.

3.4.3 Results of instructional practice 2

RQ2-a: Did the learning performance change after the science lessons?

The results of the Wilcoxon signed-rank test indicated that students' **test scores** of related knowledge was significantly improved after the lessons, which indicated the effectiveness of the instructional design on learning performance.

RQ2-b: Did each factor of CPS awareness change after the science lessons?

The results of Wilcoxon signed-rank test indicated that students' ***Task Regulation*** in cognitive CPS awareness was significantly improved after the lessons. However, no significant differences were found for other factors.

RQ2-c: What were the relationships between the changes in learning performance, changes in CPS awareness, and learning motivation in science lessons?

In order to find out what potential factors could mutually affect CPS awareness and learning performance, Spearman's Rank Correlation Coefficient was used to explore the relationships between factors of CPS awareness, learning performance, and motivation for science learning. First, as the results indicated, learning performance improvement was significantly related to *Perspective Taking* in CPS awareness. Besides, *Perspective Taking* in the social dimension was positively related to *External Causality* and *Exogenous Attribution* (summarized as *External motivation*) in motivation. Therefore, these factors were considered effective and should be considered in the design.

Since the social dimension in CPS awareness did not improve in this instructional practice, it is necessary to pay attention to group members' interaction, and reconsider problem-solving activities that motivate students to solve problems collaborating with others.

The correlation analysis also showed that students' external motivation had a positive effect on their awareness regarding taking others' contributions into one's own consideration and rethinking the problems. Compared with the case of *Immunity*, students were not familiar with the case of *Limnic Eruption*, which led to the decrease of students' curiosity and interest in the contents.

3.5 Design and assessment of instructional practice 3

3.5.1 The design of instructional practice 3

According to the results of instructional practice 2, the learning performance and *Task Regulation* awareness were improved through the CPS-based science lessons. However, the social dimension in CPS awareness did not change after the lessons. According to the previous studies (e.g., DeWitt and Siraj 2010; Wendt and Rockinson-Szapkiw 2015), to improve the effectiveness of collaborative learning, it is critical to ensure sufficient time for discussion and collaborative work in science education. In instructional practice 2, students were required to search for the necessary information on the Internet. However, since students were not familiar with the contents, the time for discussion and group work was limited. Therefore, in this design, we provided students with digital learning materials to help them focus on the necessary information and improve the efficiency of collaborative learning. The learning materials were provided through the BookRoll system.

Moreover, some learning motivation factors were identified, which were related to the improvement of CPS awareness. Therefore, instructional practice 3 was designed based on previous practice results, and mainly aimed at revising the design about improving the social dimension of CPS.

This instructional practice was also designed based on the CPS process (Hesse et al., 2015), considering influential motivation factors related to learning performance and CPS awareness. In order to support students' social activities in the lessons, two systems were used, Moodle system for e-learning and BookRoll system for reading digital learning material. Students were asked to complete the questionnaires and tests and submit the solution to each problem on Moodle system. All solutions submitted would be opened and shared with the entire class to understand their group members' state and group progress and receive feedback from the teacher and other members. The BookRoll system was used as the digital learning material reader system to provide students with information on genetic diseases during the lesson. The BookRoll interface is shown in Fig. 4.

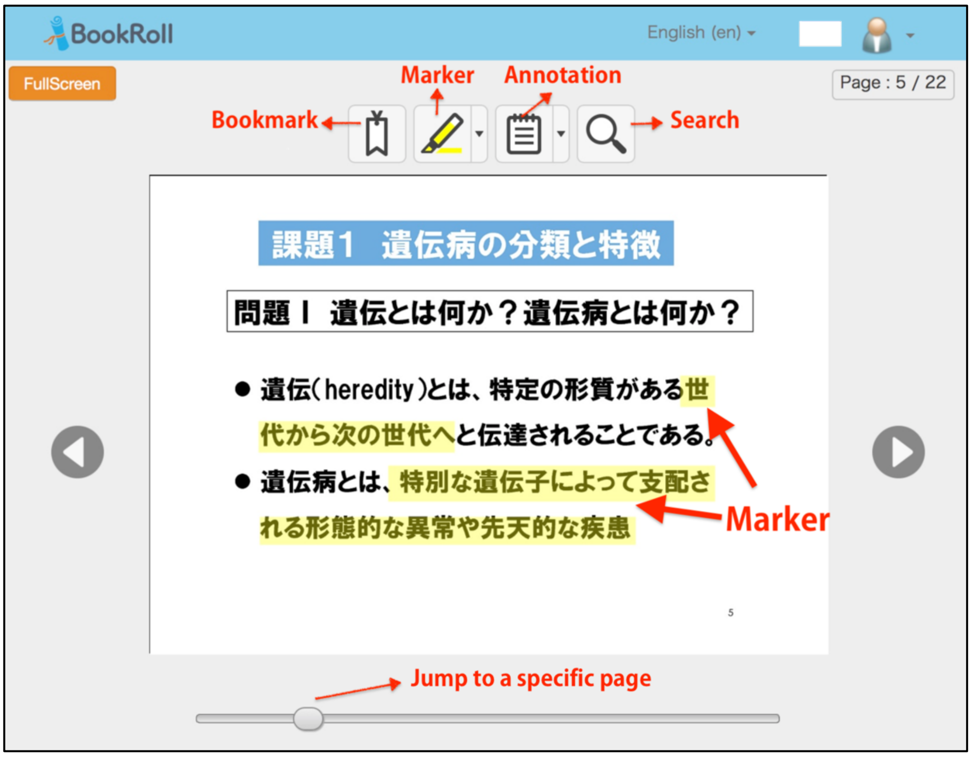


Figure 4. The interface of BookRoll system in instructional practice 3

The system's functions are described as listed.

- *Page change (Next/Previous) function*: Jumping to a specific page.
- *Marker (highlighting) function*: Highlighting text within a page.
- *Annotation function*: Adding annotation within a page.
- *Bookmark function*: Posting bookmarks in learning materials.
- *Search function*: Search learning materials using keywords.

However, students were only asked to use the marker function during this study, which meant highlighting the selected texts they felt were important, or they did not understand. All the operations on the BookRoll system were collected to represent students' learning behaviors regarding reading learning materials.

In this practice, the effectiveness of the CPS learning was examined. Moreover, the relationships between CPS awareness, learning performance, and learning motivation were examined to find out what factors would influence the improvement of learning performance and CPS awareness.

Therefore, the following research question were set:

RQ3-a: Did the learning performance change after the science lessons?

RQ3-b: Did each factor of CPS awareness change after the science lessons?

RQ3-c: What were the relationships between the changes in learning performance, changes in CPS awareness, and learning motivation in science lessons?

3.5.2 Context and procedure of instructional practice 3

The theme of instructional practice 3 was *Genetic Diseases*, in which students were asked to identify the reason for Scottish Fold cats' special ears and find meaning in the associated genetic disease. The purpose of this lesson was to investigate the reason behind Scottish Fold cats' characteristics, better understand their genetic diseases and the hereditary and environmental factors that affect congenital conditions. Finally, students were asked to decide how to treat Scottish Fold cats properly based on bioethical principles. Therefore, the final goal of the problem was to identify the advantages and disadvantages of raising or neutering Scottish Fold cats and propose a solution for how to treat them based on the agreement within the group. The problems were designed to encourage students to reflect on their attitudes and appropriate measures for people or animals with genetic diseases. In this lesson, students learned scientific knowledge about genetic diseases through the inquiry process (science), they used functional tools on the BookRoll system to understand the contents of the lessons, searched information on the Internet, and used Moodle system to share the information and the solutions to other students (technology), and students were required to develop a solution to make an appropriate decision for the animals with genetic diseases as the final product for CPS learning (engineering). However, mathematics-related knowledge and skills were not designed in this practice. One part of the learning materials is presented in Figure 5.

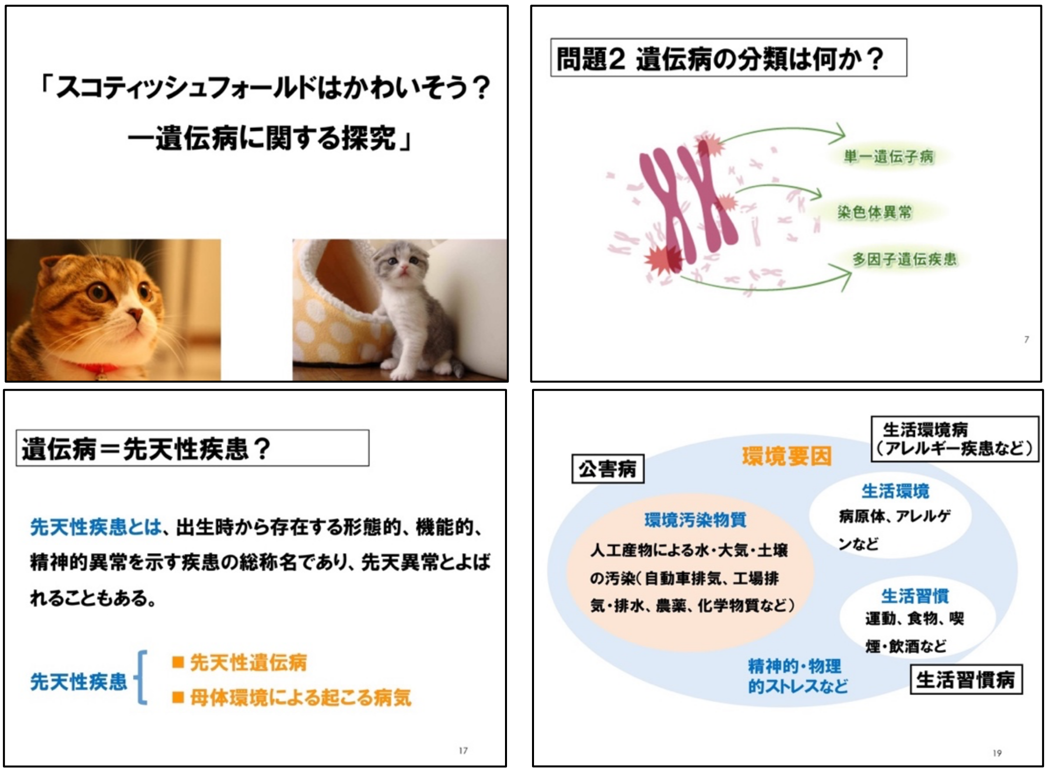


Figure 5. A part of the learning materials in instructional practice 3

As the final product of CPS learning, each group was required to make a presentation about whether to let the Scottish Fold cats take sterilization. The teacher assessed whether the agreement of the group was correct and provided feedback and comments on their presentation. The solutions could be judged as correct as long as students state the reasonable reasons for their decisions. The reasons include the advantages (for example, Scottish Fold cats having severe genetic disease which is harmful to their health) and disadvantages (for example, if the Scottish Fold cat has other diseases which cause it not suitable to take sterilization) of taking sterilization.

This study was conducted in a twelfth-grade science class in two lessons over 100 minutes, with the participation of 25 students. The procedure of the data collection was the same as in experiment 2. The learning logs on the BookRoll system were also collected to represent students' learning behaviors, such as the frequency they turned to the next/previous page, jumped a page, and added/deleted markers.

3.5.3 Results of instructional practice 3

RQ3-a: Did the learning performance change after the science lessons?

The results of the Wilcoxon signed-rank test showed that students' **test scores** were significantly improved after the lessons, which indicated the effectiveness of the science lessons on the improvement of learning performance.

RQ3-b: Did each factor of CPS awareness change after the science lessons?

No significant differences were found in the improvement of CPS awareness at the significant level of $p<0.5$.

RQ3-c: What were the relationships between the changes in learning performance, changes in CPS awareness, learning motivation, and learning behaviors in science lessons?

According to Spearman's Rank Correlation Coefficient, there is a positive correlation between *Participation* awareness in CPS and *Mastery* in motivation, positive correlations between *Perspective Taking* awareness with *Curiosity*, *Internal Causality*, and *Exogenous Attribution*, positive correlations between *Social Regulation* awareness with *Challenge, Curiosity, Mastery,* and *Internal Causality*, and a positive correlation between *Learning and Knowledge Building* awareness with *Curiosity*.

As for learning behavior factors, no correlation was found between learning behaviors with learning performance improvement or CPS awareness at the significance level of $p < 0.05$.

As for future work, first, in this instructional practice, the Scottish Fold cat was used as the case for *Genetic Diseases*. However, since few students were familiar with the Scottish Fold cats and lacked the related knowledge, it was difficult for them to solve the problem in the limited time. According to students' free descriptions in the post-questionnaire, many students pointed out that "there were too many difficult words." Although the learning performance was improved after the lessons, the cognitive dimension in CPS showed no changes. Therefore, it is necessary to reconsider the difficulty of knowledge related to the theme, the design of the problems, and the method of presenting learning materials.

In addition, students' learning behaviors during the lessons were collected and analyzed to find out what learning behaviors were related to the effectiveness of the CPS-based science lessons. However, no correlation was found between learning behaviors with other factors. One possible reason is that students were not provided with sufficient time to be familiar with the system and use their cognitive strategies to read learning materials. Therefore, in the subsequent design, the specific use of the functional tools on BookRoll system should be considered and instructed.

3.6 Design and assessment of instructional practice 4

3.6.1 The design of instructional practice 4

Instructional practice 4 was designed based on the results of instructional practice 3 and mainly aimed at improving the cognitive dimension of CPS by the support of functional tools on BookRoll system. Therefore, instructional practice 4 was also designed based on the CPS process (Hesse et al. 2015), considering essential motivation factors. Moreover, the learning materials were also provided through the BookRoll system, and students were instructed about how to use functional tools when reading learning materials.

More operations were collected and analyzed to understand students' learning behaviors during the science lessons and determine what factors of learning motivation (learning awareness) and learning behaviors (related to learning strategies) would have effects on the learning performance and CPS awareness.

Therefore, in this practice, the following research questions were set:

RQ4-a: Did the learning performance change after the science lessons?

RQ4-b: Did each factor of CPS awareness change after the science lessons?

RQ4-c: What were the relationships between the changes in learning performance, changes in CPS awareness, learning motivation, and learning behavior in science lessons?

Moreover, since the individual cognitive differences of learners would affect their acquisition of new knowledge (Dinsmore et al., 2014), the difference between high performers and low performers was examined regarding the learning effectiveness. The research question was:

RQ4-d: Between high and low learning performers, what was the difference in motivational and behavioral factors that influence learning performce and CPS awareness?

Finally, students' CPS awareness was examined by the questionnaires, which was subjective and represented students' perception only. In order to assess students' CPS skills based on an actual and objective perspective, the dialogue analysis was conducted to analyze students' discussions during CPS activities.

RQ4-e: How did students display CPS skills during the discussion?

3.6.2 Context and procedure of instructional practice 4

The theme of this instructional practice was Limnic Eruption, which was the same as instructional practice 2, and revised based on the previous results. The purpose of this instructional practice was to investigate the mechanism of limnic eruptions and facilitate students' thinking on what they can do and should do when facing such disasters using science. In order to make the tasks proceed more smoothly, three questions were designed for students to discuss with each other. (1) What is the mechanism of limnic eruptions? (2) Could it possibly occur in Japan? (3) What should we do or what can we do when we face such a disaster? To solve the first problem, students needed to understand where CO_2 comes from and the relationships between the solubility of CO_2 in water and air temperature and pressure. In order to figure out the second problem, students should understand the mechanism and related knowledge of the first problem, compare the climate and weather characteristics of Cameroon and Japan, and finally make a judgment as to whether a limnic eruption would occur in Japan. The last problem was designed to help them understand the effect of natural disasters and promote their awareness to take proper measures to minimize the damage and loss caused by inevitable disasters. The final goal of the problem was the same as Instructional practice 2, which is to propose a manual of disaster reduction based on the consensus within the group. One part of the learning materials is presented in Figure 6.

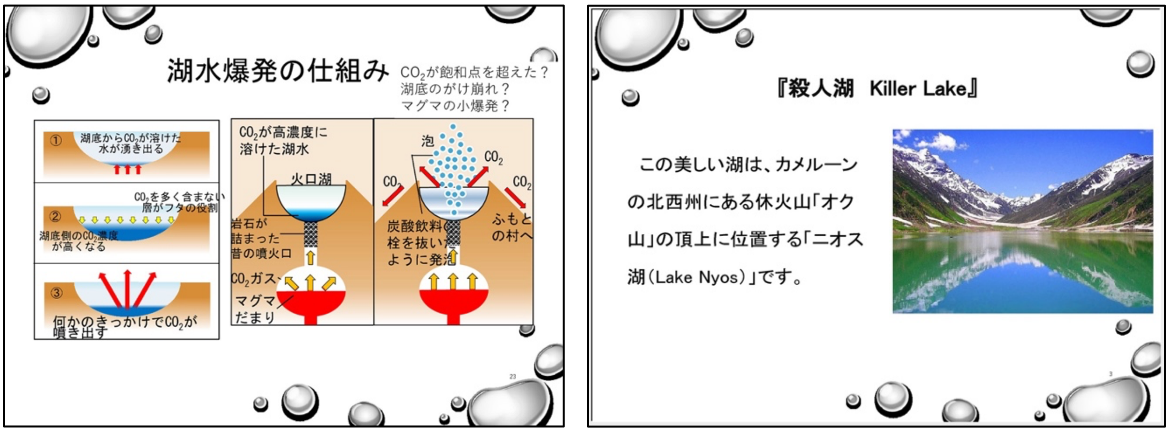


Figure 6. A part of the learning materials in instructional practice 4

In order to support students to solve the problems, some driving problems were designed to help them understand and construct related knowledge. For example, in this lesson, the primary purpose is to explore the mechanism of limnic eruptions, which is related to the solubility of CO_2.

Students need to understand the relationships between the solubility of CO_2 with the temperature and pressure. First, students were provided the figures about the relationships between the solubility of CO_2 with the temperature and pressure. Then students were provided examples related to their real-life (for example, what will happen when open the bottle of carbonated water? Why will the bottle carbonated water become harder in summer?), and they were asked to understand the principle regarding the problems. Then, they need to understand the principle and use this principle and knowledge to explain the figure. Finally, students were asked to solve the main problem based on the understanding of the above knowledge.

The topic was the same as instructional practice 2, and the problems in this lesson were also designed to encourage students to reflect on their attitudes and appropriate measures when facing such unavoidable disasters. In this lesson, students learned scientific knowledge about CO_2 through the inquiry process (science). Different from instructional practice 2, in which students were mainly required to search for the necessary information on the Internet, in this practice, the related contents and sub-tasks were provided to students through BookRoll system to help students understand each sub-task. Students used functional tools on the BookRoll system to understand the contents, searched information on the Internet, and used Moodle system to share the information and the solutions to other students (technology). They were also required to develop a solution to take appropriate measures for this natural disaster and designed a disaster mitigation manual as the final product for CPS learning (engineering). Finally, different from the previous three practices, in this practice, students used mathematics-related knowledge and skills to clarify and understand the relationships between the CO_2 solubility with temperature and pressure.

Each group was required to make a presentation as the final product of CPS learning. The criteria of the assessment for students' presentations were the same as instructional practice 2.

This study was conducted in a tenth-grade science class in three lessons (150 minutes), with the participation of 31 students. The data collection procedure was the same as in instructional practice 3.

3.6.3 Results of instructional practice 4

RQ4-a: Did the learning performance change after the science lessons?

Wilcoxon signed-rank test was used to assess the significance of changes in the pre-post tests regarding the knowledge in the lessons. However, no significant differences were found for the improvement of learning performance. Based on these results, it is hard to say that students' related knowledge improved during this science lesson.

RQ4-b: Did each factor of CPS awareness change after the science lessons?

Wilcoxon signed-rank test was used to assess the significance of changes in the pre-post CPS questionnaire's results. However, no significant differences were found for the improvement of CPS awareness.

Due to the large proportion of students whose scores decreased from the pre-test to the post-test, it is inferred that there was an individual cognitive difference in the class, and that low-performance students could not understand the lesson well. Thus, it is not difficult to imagine that not all the students could actively participate in the learning and that low-performance students could not decide whether others' opinions and viewpoints were correct or fill in the gaps of insufficient information. Thus, it was not easy for them to improve their awareness regarding social and cognitive dimensions.

RQ4-c: What were the relationships between the changes in learning performance, changes in CPS awareness, learning motivation, and learning behavior in science lessons?

According to Spearman's Rank Correlation Coefficient, there is a negative correlation between the learning performance improvement and *Learning and Knowledge Building* awareness in CPS.

As for the correlations between CPS awareness and motivation, positive correlations were found between *Participation* awareness and *Perspective Taking* awareness with *Enjoyment* in motivation, respectively, *Social Regulation* awareness with *Mastery*, *Learning and Knowledge Building* awareness with *Internal Causality*, which should be considered in the design.

As for learning behavior factors, *Delete Marker* behavior was found positively related to *Social Regulation* awareness in the social dimension. It is indicated that the use of marker tool can be expected to improve social awareness in CPS.

RQ4-d: Between high and low learning performers, what was the difference in motivational and behavioral factors that influence learning performance and CPS awareness?

In RQ 1, there were no significant differences in students' learning performance improvement during the lesson. It was indicated that the effectiveness regarding learning performance was not proved through the instructional design. Dinsmore et al. (2014) argued that the success or failure of applying knowledge to other situations is related to learners' individual differences, such as prior knowledge or experience. Thus, it is assumed that the individual cognitive differences of learners would affect their acquisition of new knowledge. According to their specific pre-test and post-test scores, respectively, there were 13 students (41.9% of the 31 students) whose post-test score was lower than their pre-test score. It is considered that many students who answered correctly on the pre-test as actually not making sense of the problems well. In order to explore specific reasons, the students were divided into two groups, high-performance and low-performance, according to their pre-test scores, to see if their individual differences affected their learning effectiveness. Spearman's Rank Correlation Coefficient was used to investigate the relationships among CPS awareness with learning motivation and learning behaviors and compared the results of high-performance and low-performance groups. The students who gained a pre-test score in the top 25 percentile (first quartile) were categorized into the high-performance group (N = 9, Mean = 8.3), and those who gained a pre-test score in the bottom 25 percentile (third quartile) were classified as the low-performance group (N = 10, Mean = 4.1). The results indicated a difference between the high and low performers. First, regarding the difference in CPS awareness, the *Perspective Taking* awareness in the **high-performance group** (Mean = 2.22, SD = 3.12) is significantly higher than the **low-performance group** (Mean = -0.90, SD = 1.97). It was indicated that students' prior knowledge had an influence on the improvement of *Perspective Taking* awareness.

Second, as for the differences of correlations in the two groups, in the **low-performance group**, there were positive correlations between learning performance improvement with *Social Regulation* awareness in CPS, while in the **high-performance group,** there was no correlation found regarding learning performance improvement.

As for the correlations between CPS awareness with motivation and learning behaviors, in the **low-performance group**, positive correlations were found between *Social Regulation* awareness in the social dimension with *Challenge, Curiosity, Mastery, Internal Causality, Endogenous Attribution,* and *Enjoyment* in motivation, and *Delete Marker* behavior respectively. In addition, there is a negative correlation between *Learning and Knowledge Building* awareness in the cognitive dimension and *Exogenous Attribution* in motivation. In the **high-performance group**, positive correlations were found between *Participation* awareness in the social dimension and *External Causality*, *Learning and Knowledge Building* awareness and *Internal Causality*, and *Task Regulation* awareness in the cognitive dimension, and *Delete Marker* behavior. The results indicated that low performers' learning motivation and learning behaviors were correlated with the social dimension of CPS awareness, while those of high performers were correlated with their cognitive awareness. It can be inferred that high performers' intrinsic motivation and CPS cognitive awareness in such factors as *Task Regulation* and *Learning and Knowledge Building* mutually influence each other. On the other hand, for low performers with high exogenous attributions (in pursuit of good scores or praise from teachers), it may still be challenging to integrate and construct knowledge due to their poor cognitive skills. Nonetheless, it is possible that even though they clearly understand the importance of knowledge building and integration, they still have low extrinsic motivation for their science learning. The results are consistent with the discussion above, which indicates that high performers focus on the cognitive dimension during CPS activities, while low performers benefit more from social activities.

RQ4-e: How did students display CPS skills during the discussion?

In RQ4-d, the Spearman's Rank Correlation Coefficient revealed significant positive correlations between the behavior of deleting markers with *Task Regulation* awareness in CPS in the high performer data and *Social Regulation* awareness in CPS in low performer data. Since students were required to delete the markers when they understood the contents or changed their ideas, the behavior of deleting markers could be linked with students' reflection activities during the lecture. It is indicated that high performers focus on cognitive activities, while low performers focus on social activities during CPS learning. In order to investigate whether high and low performers focus on different CPS dimensions during the group discussion, the dialogue analysis was conducted to understand how students displayed these CPS skills. I analyzed the dialogue data during students' group discussion and categorized dialogue thread concerning *Task Regulation* and *Social Regulation* awareness.

According to the CPS framework with reference to the Hesse et al. (2015), there are four elements in Social Regulation factor, which are negotiation, self-evaluation (meta-memory), transactive memory, and responsibility initiative, and six elements in Task Regulation factor, which are problem analysis, sets goals, resource management, flexibility and ambiguity, collects elements of information, and systematicity. The elements and the indicators of *Social Regulation* and *Task Regulation* were listed in **Table 3**. However, no transactive memory behavior, flexibility and ambiguity or systematicity behavior was found during the discussion. To explain the findings in more depth, seven examples were described in detail.

Table 3 Elements and indicators in *Social Regulation* and *Task Regulation* awareness

CPS awareness	**Element**	**Indicator**
Social Regulation	Negotiation	Achieving a resolution or reaching a compromise
	Self-evaluation	Recognizing own strengths and weaknesses
	Transactive memory	Recognizing the strengths and weaknesses of others
	Responsibility initiative	Assuming responsibility for ensuring parts of the task are completed by the group
Task Regulation	Problem analysis	Analyzing and describing a problem in familiar language
	Sets goals	Setting a clear goal for a task
	Resource management	Managing resources or people to complete a task
	Flexibility and	Accepting ambiguous situations

	ambiguity	
	Collects elements of information	Exploring and understanding elements of the task
	Systematicity	Implementing possible solutions to a problem and monitoring progress

***Social Regulation*—Negotiation**

Example 1

1. S1: I think carbon dioxide is at the bottom of the lake. Because it is denser than air.

2. S2: Really?

3. S1: Yes, it is written that "denser than air." (showing others the information on the Internet).

4. S2: I see.

5: S3: So we should use a downward delivery method (to collect carbon dioxide).

6. S1: Yes. But it can also be collected by downward displacement of water.

7. S4: Yes, both of them can be used.

8. S3: No, downward displacement of water can't be used. (Because) carbon dioxide dissolves in water.

9. S4: You are right.

In Example 1, students in this group showed a negotiation part around the "did CO_2 accumulate at the top or the bottom of the lake" issue. According to the CPS framework, the indicator of Negotiation is awareness activities for "achieving a resolution or reaching a compromise." In Example 1, all students agreed with the density of CO_2, but showed disagreement in the collection methods of CO_2, which is related to the property of CO_2. In Line 6 and 7, S1 and S4 thought both downward delivery and downward displacement of water method could be used to collect CO_2, but S3 pointed out their mistakes and explained the reason (in Line 8). In Line 9, it is indicated that at least S4 reached an agreement with S3's opinion.

***Social Regulation*—Self-evaluation (Meta-Memory)**

Example 2

10. S3: (Searching the information on the Internet) It may be, at the bottom…

11. S1: Why?

12: S3: It was written here, but I am not sure. I can only find the English webpage. I am not good at searching.

The indicator of Self-evaluation is "recognizing own strengths and weaknesses," which was not used very frequently in the discussion. In this example, S3 tried to search the answer for "did CO_2 accumulate at the top or the bottom of the lake?", but recognized the weaknesses of his searching skills (in Line 12).

***Social Regulation*—Responsibility initiative**

Example 3

13. S5: Let's start with this page.

14. S6: Let's start with…which page?

15. S8: Page 19.

(…)

22. S5: It was written here. (Reading the texts) "The solubility of the carbon dioxide in water decreases as the temperature increases and pressure decreases. Therefore, if you open a can or bottle of soda, there is a great decrease in pressure over the liquid, so the carbon dioxide starts to leave the liquid very rapidly." I have no idea about these.

23. S6: Which page?

24. S5: Page 20.

25. S7: The temperature becomes lower, when the depth in the lake increases.

26. S6: Yes. That's right. So compared with the top of the lake, the temperature of the bottom of the lake is lower.

27. S7: On page 20, it was written that "when the temperature rises, carbon dioxide is easier to be released into the air."

28. S6: I see.

Responsibility initiative includes the indicator "assuming responsibility for ensuring parts of the task are completed by the group," such as assuming group responsibility as indicated by use of first-person plural, completing activities, and reporting to others. In Line 3 in Example 1, S1 searched information about the density of CO_2, and reported the information to others. As shown in Example 3, students were discussing the question "what is the mechanism of limnic eruption?." In Line 13, S5 suggested beginning the task together, making everyone focus on the learning materials. In Line 22 and 27, when S5 and S7 found the related contents on the learning materials, they shared these contents with other members. Since students conducted behaviors of providing information on the BookRoll system (for example, in Line 15, 22, and 24), it is indicated that students utilized BookRoll system tools with their responsibility initiative awareness.

***Task regulation*—Problem analysis**

Example 4

29. S9: Do you know the meaning of the question?

30. S10: I think it means when and how did limnic eruption occur.

(…)

59. S11: What does "the temperature increased" mean? Does it mean that the temperature is high?

60. S10: No, it means there is a temperature difference, occurred in the lake.

The indicator of Problem analysis is "analysing and describing a problem in familiar language." In Example 4, students were discussing the question "what is the mechanism of limnic eruption?." In Line 30, S10 explained to S9 the meaning of "mechanism" in other familiar words that were easy to understand. In Line 60, when S11 misunderstood the meaning of "temperature increased," S10 explained the correct meaning with another expression.

***Task regulation*—Sets goals**

Example 5

61. S13: So, what should we search first? Why did carbon dioxide occur at the bottom of the lake?

62. S14: Yes, that's a good idea.

The indicator of Sets goals means "set a clear goal for task." However, there was only one example for sets goals found, which indicated the insufficient of students' setting goals awareness during CPS learning. As shown in Line 61, only S13 suggested to think about the plan to solve the problem.

***Task regulation*—Resource management**

Example 6

63. S11: What' the difference between Japan and Cameroon?

64. S10: I don't know. Where is Cameroon?

65. S9: What about searching the information on the Internet?

66. S11: Good idea.

(…)

82. S10: What is the feature of temperature in Cameroon?

83. S9: Let me search it on the Internet.

84. S12: It was written on the learning materials. Page 26.

Resource management indicator includes "managing resources or people to complete a task," such as allocating people or resources or suggesting that people or resources be used. During the discussion, behaviors of allocating or suggesting resources (such as the information on the Internet and the learning materials on the BookRoll system) were found. As shown in Line 65 and 83, S9 suggested utilizing the resources on the Internet twice, and in Line 84, S12 used the learning materials to solve the problem. Since resource management behavior was found during the use of the BookRoll system, it can be inferred that the utilization of BookRoll system tools is correlated with students' resource management awareness.

***Task regulation*—Collects elements of information**

Example 7

85. S13: (Reading the texts of the feature of temperature in Cameroon). Yes, I accept.

86. S14: So Japan is similar to Cameroon?

87. S16: No, read this. "There are four seasons in Japan." But Cameroon is different. See this table.

The indicator of Collects elements of information is "exploring and understanding elements of the task," such as identifying the need for information, or the nature of the information related to activities. In Line 85, S13 acknowledged the usefulness of the texts after reading. In Line 87, S16 selected the most useful information and identified the meaning of the table.

3.7 Conclusions: Important factors of effective CPS process

This chapter conducted four practical experiments to identify what factors should be considered in the CPS process in science education. The design of the CPS process in the science lesson and the results of four practices are shown in Figure 7. The effectiveness of the practical experiments was examined from two aspects, the CPS design, and STEM learning outcomes.

Regarding the CPS design, as the results, the design of CPS-based science learning effectively improved ***Participation***, ***Task Regulation***, and ***Learning and Knowledge Building*** awareness in CPS.

In order to identify the potential factors that influenced these three types of CPS awareness and the other two types of awareness, the relationships between CPS awareness with motivation and learning behaviors were examined. The results indicated that motivational factors including *Challenge*, *Curiosity*, *Mastery*, *Enjoyment*, *Internal Causality*, and the use of Marker tools influenced the CPS awareness in the lessons. In order to improve students' all factors in CPS awareness in STEM learning, it is necessary to consider these factors in future work.

Regarding the STEM learning outcomes, the aim was to acquire related knowledge and apply the knowledge to authentic problem-solving. The outcomes concerning this aim were assessed through the final presentations, tests, and dialogue analysis. First, students acquired and constructed related knowledge through the lectures and group discussion and solved problems by reaching an agreement within the groups. The teachers assessed all the groups' solutions during the presentations and revised the knowledge by pointing out the discrepancies between the final solution and their reasons. Second, pre-post tests were conducted to examine the acquisition and application of the related knowledge. In instructional practices 2 and 3, the learning performance was significantly improved after the lessons. However, in instructional practice 4, the learning performance was not significantly changed after the lessons. Regarding the reasons, according to the results, there were apparent differences in the effects of CPS awareness on the learning performance between the high-performance group and low-performance group, which indicated the influence of students' prior knowledge on the acquisition of new knowledge through CPS activities. In future work, students' prior knowledge should be considered one element in the instructional design, including providing enough background knowledge or considering the group formation. Finally, to examine how students used their CPS skills to construct knowledge, students' utterances and actions during the group work were analyzed by the dialogue analysis. However, the dialogue analysis was only conducted in instructional practice 4. For example, how students used cognitive skills to collect and analyze the elements of problems, set goals to solve problems, and manage the available information to solve authentic problems were identified.

In each experiment, students were required to answer the free text questions in the post-questionnaire regarding their reflection and perception of lessons. As for their perception of the topic and problems they solved, many students showed their interest for the four topics since "the disease of cold is very common, and it is important to understand the mechanism of the disease" (instructional practice 1). Students also felt the *Limnic Eruption* topic "is interesting to explore the disaster of other countries, and compare it with Japan" (instructional practice 2), and they have learned a lot about the "the crater lake and environment in Japan, which we (students) have few chances to learn in usually learning" (instructional practice 4). However, although students thought the topic of Scottish Fold cats was interesting because "the cats are close to the daily life," they still felt "the knowledge related to the genetic disease is too difficult" (instructional practice 3). Therefore, I concluded students' perceptions of the topic and took their perceptions into consideration. In future work, we should help students construct understanding of the related knowledge, such as providing hints or similar examples before solving the problems. Moreover, it is important to encourage students to reflect on the significance and implications of the problems, such as how they could use the solutions or methods to improve their lives.

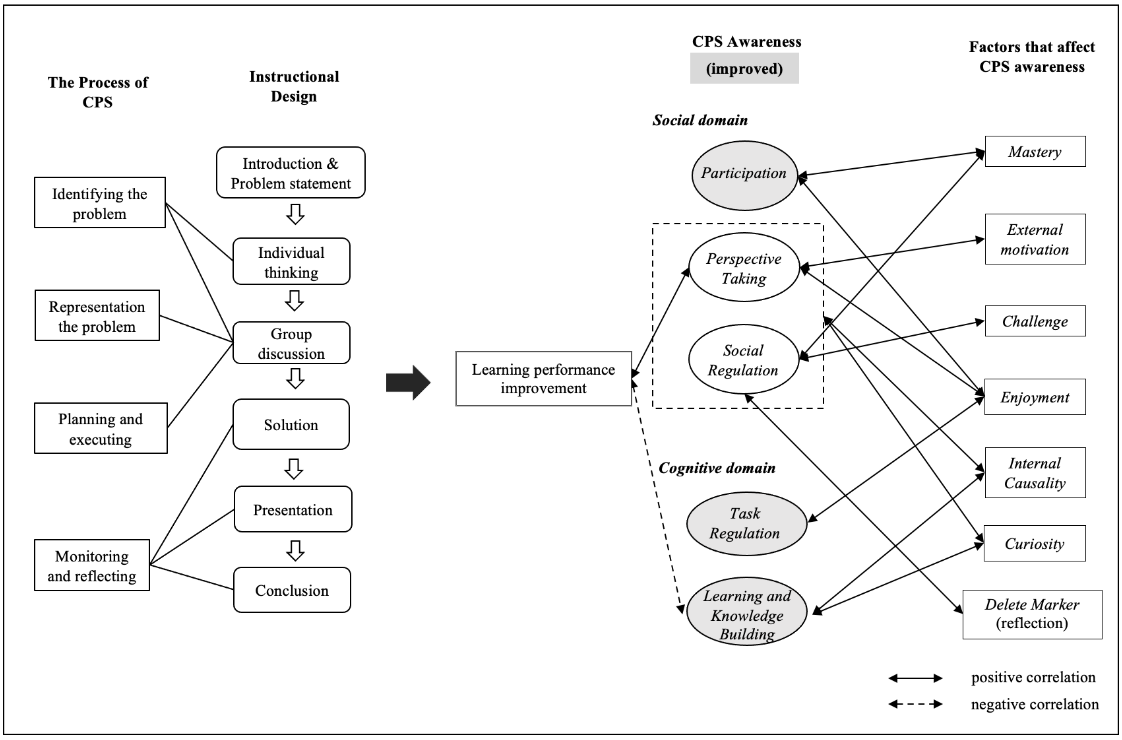


Figure 7. The design and the results of four science practices

3.8 Challenges of these four instructional practices

Although the above practices indicated essential factors regarding the design of CPS learning, there are still some challenges that remain. First, since authentic problems always contain knowledge and skills of multiple fields, it is necessary to integrate the knowledge and skills of multiple fields into the course rather than a simple science field (Kelley and Knowles, 2016). Therefore, one of the future works is to emphasize the integration of STEM fields and the use of STEM learning strategies.

Second, from the results above, it was found that individual thinking influenced CPS learning. Therefore, in future work, individual thinking activities during the whole learning process should be considered. In other words, the individual learning behaviors both in and out of the class should be analyzed.

Third, although the BookRoll system was used to help students learn digital materials and collect their learning behaviors during the reading, there were few learning behaviors related to learning performance and CPS awareness due to the limited types of learning logs and individual learning time. Therefore, in future work, more learning behaviors should be collected and analyzed in a longer experimental duration.

Chapter 4: Instructional practice for Integrating STEM Strategies into Collaborative Problem Solving Process in STEM Education

4.1 The aim of instructional practice 5

In instructional designs 1–4, CPS-based science lessons were designed, and the effectiveness of the instructional designs was assessed. Moreover, the relationships between different factors were examined to clarify the potential factors influencing learning performance and CPS awareness. However, as we discussed in Chapter 3, some challenges remain.

In instructional practice 5, the aim is to design a CPS-based STEM course based on the previous results and integration of STEM disciplines. The lessons were designed based on the CPS process, the integration of four STEM disciplines, and the use of STEM learning strategies. This design aims to integrate the use of STEM learning strategies into the CPS process in the context of STEM. In addition, since individual thinking influences CPS learning, students were asked to conduct individual learning activities, including preview and review; the individual learning behaviors were analyzed. The revised design of the CPS process in the STEM lesson is presented in Figure 8.

Similar to instructional practices 1–4, designing and assessing instructional practice 5 include two aspects, the effectiveness of CPS design and the outcomes of STEM lessons. First, regarding the CPS design, the aim of four instructional practices was to improve students' CPS skills. Second, concerning the outcomes of STEM lessons, the aim of this instructional practice was to acquire related knowledge and apply the knowledge to authentic problem solving.

As one of the goals of STEM education, students are expected to acquire knowledge during the activities of solving problems with authentic contexts or apply them to authentic problems (Holmlund et al., 2018). Therefore, as the first and second research questions, the difference in pre-posttests and questionnaires was analyzed to examine whether the learning performance and CPS awareness were changed after the STEM lessons.

RQ5-a: Did the learning performance change after the STEM lessons?

RQ5-b: Did each factor of CPS awareness change after the STEM lessons?

The present practice aims to examine the relationships between learning performance and learning behaviors, in order to determine what kind of learning behaviors should be recommended or paid attention to during STEM learning. Meanwhile, in order to understand the ways to instruct students to use effective learning strategies to acquire knowledge, it is necessary to identify what kind of STEM learning strategies would influence learning performance. Moreover, since this was not the first time students experienced learning CO_2-related content and participating in this form of group work, students might have different prior knowledge and CPS awareness, which could influence the final results. Therefore, considering the different scores of students' pre-test and CPS pre-questionnaire, it was not suitable to only consider the final results of learning performance and CPS awareness. Therefore, as the third research question, the relationships between the change in learning performance and CPS awareness, with learning behaviors and STEM learning strategies, were examined to find out the potential factors that were related with the change in learning performance.

RQ5-c: Which factors of STEM learning strategy and learning behaviors had relationships with the change in learning performance?

Some of the previous studies cited above showed that it is important to identify the characteristics of all the sub-factors of CPS skills when developing CPS skills, such as what kinds of relationships these sub-factors have with other learning factors. Therefore, the fourth research question aimed to examine the relationships between the improvement in CPS awareness with behavioral and strategic factors.

RQ5-d: Which factors of STEM learning strategy and learning behaviors had relationships with the change in CPS awareness?

In order to understand how students conduct these behaviors, it is necessary to associate these learning behaviors with the learning strategies they used during STEM learning. Next, students and instructors could be provided with some suggestions on the learning behaviors associated with the improvement in learning performance and CPS awareness. Instructors could also be provided suggestions on how to encourage students to conduct these learning behaviors by using related learning strategies.

RQ5-e: What were the relationships between STEM learning strategy and learning behaviors?

Students' CPS awareness was examined by the questionnaires, which were subjective and represented only students' perception. In order to assess students' CPS skills based on an actual and objective perspective, the dialogue analysis was conducted to analyze students' discussions during CPS activities.

RQ5-f: How did students display CPS skills during the discussion?

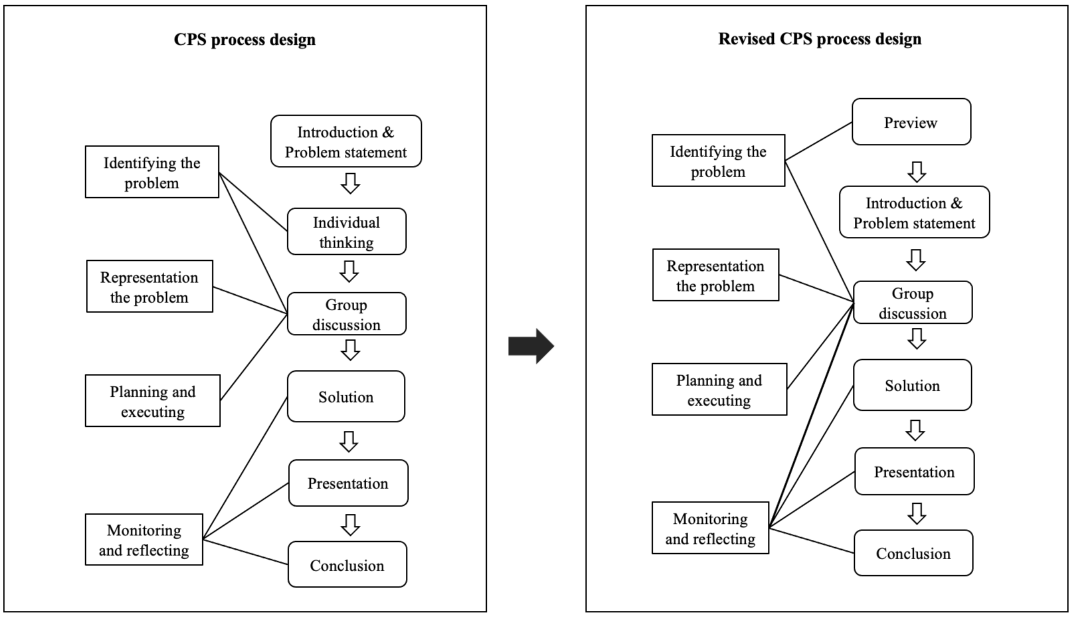


Figure 8. The design of CPS process in Instructional practice 5

4.2 Methods

4.2.1 Context

According to the results of instructional practices 1~4 regarding the effective motivation factors, it is important to provide students with the theme and problems they are interested in, set the problems with different difficulty levels, and provide them with sufficient information. Thus, based on the discussion with the teachers, the theme *Limnic Eruption* was used, which was revised based on instructional practices 2 and 4. The purpose of the lesson was to investigate the mechanism (reason) of the limnic eruption and to design a manual of disaster mitigation, including knowledge of natural disasters, the relationship between the environment and human beings, and what to do when faced with such natural disasters. The final goal of the problem was to propose a manual of disaster reduction based on the consensus within the group.

Four STEM disciplines were integrated into this lesson:

Science: Students need to understand CO_2-related scientific knowledge, including the nature and generation process of CO_2 and the solubility of CO_2, and use scientific knowledge and skills to solve the applied problems.

Engineering: Students are asked to design a manual of disaster mitigation to integrate their multidisciplinary knowledge and skills to problem-solving and improve their understanding of scientific and mathematical knowledge by practicing their application.

Mathematics: Students are required to use their mathematical knowledge and skills to perform the respective calculations in CO_2-solubility-related problems and make a judgment as to whether the information provided by the Internet is correct.

Technology: Students are asked to use Moodle and Bookroll system to support individual pre-learning and group discussion and the Internet for information retrieval. The use of technology and decision-making regarding Internet information is expected to improve students' technological literacy.

In order to make the tasks proceed more smoothly, five questions were designed for students to discuss with each other. (1) Where was CO_2 formed in Lake Nyos? (2) Where did more CO_2 dissolve and accumulate in the Lake Nyos, the surface or the bottom? Why? (3) According to Wikipedia, there is about 90 million tons of CO_2 dissolved in Lake Nyos (Wikipedia: Lake Nyos, Japanese version). How much pressure does it take for 90 million tons of CO_2 to dissolve in Lake Nyos at 20 °C? (4) In summary, what is the mechanism of limnic eruptions? (5) Could Limnic Eruption possibly occur in Japan?

Before each lesson, students were required to read the related learning materials and to highlight and record the contents they did not understand or thought were important. In the first week, the teacher introduced the Limnic Eruption disaster and explained the difficult contents according to what students highlighted (pre-learning). Subsequently, students worked on questions 1 and 2 by searching and analyzing the information and discussing with others. Students were divided into small groups (three~four students per group) according to their seats or student numbers to minimize the heterogeneity of the group composition. Students were asked to discuss the highlights and annotations they added during pre-learning. Next, all groups made a presentation about their conclusion and received feedback from the teacher and other students. During the second and the third week, students performed pre-learning and group discussions in the same form and worked on questions 3~5. In the fourth week, students were asked to use the integrated knowledge and skills to design a manual of disaster mitigation and make a presentation to the whole class.

In order to facilitate pre-learning and group discussion, as well as to collect and analyze the learning behaviors of participants and pre-learning and individual thinking behaviors during group work, the BookRoll system was integrated into the design. One part of the learning materials provided through BookRoll system is presented in Figure 9. Students can access these learning materials both in class and at home, which makes it possible to collect the learning logs from when students prepare or review their lessons to understand their learning conditions. In addition, as students can use additional functions such as highlighting, annotating, and searching for keywords, these learning logs can all be collected for further analysis and instruction improvement.

Figure 9. A part of the learning materials in instructional practice 5

4.2.2 Procedure

This study was conducted in a tenth-grade science class at a private senior high school in Japan with 12 students. The situations of the experiment school are described regarding the following two aspects, the STEM teaching and learning experience and the use of technology. First, students' usual science lessons are designed and conducted based on the textbooks, focus on one main subject, and design well-defined problems for students more often than ill-defined problems. One special situation in this class was that many students aimed to get into the medical department/faculty, so their science teacher would add some medicine-related knowledge into the usual science lessons. Therefore, in this lesson, some medicine-related knowledge, such as carbon dioxide toxicity, was added to the problem design. As for students' learning, although students learned some medicine-related knowledge in the science lessons, most students did not experience STEM learning, which is designed based on multiple fields, and ill-defined problems and well-defined outcome. Second, the Moodle system (technology) was introduced in this experiment school. However, not all teachers used this system in their usual teaching. Therefore, when the systems including BookRoll and Moodle system were used in this instructional practice to support students' cognitive and collaborative activities, the guidance and practice time were provided to students.

This study was conducted between November and December 2018 and included four lessons (50 min per lesson) over four weeks (one lesson per week). In addition to the teaching hours, students were asked to read the provided learning materials on the BookRoll system and to finish the assignments.

Each group was required to make a presentation as the final product of CPS learning. The criteria of the assessment for students' presentations were basically the same as the instructional practice 2, except that in this practice, students were expected to understand the dangers of excessive carbon dioxide and how to treat carbon dioxide poisoning and develop the awareness to respect nature and the actions to protect themselves and other people based on the understanding.

Before the STEM lesson, students were introduced to the following basic STEM learning strategies (Griese, Lehmann, & Roesken-Winter, 2015).

Organizing: Organizing and summarizing the important points.

Elaborating: Connecting new scientific facts with earlier ones or practical applications.

Repeating: Learning and remembering scientific facts through repetition.

Effort: Making efforts to learn science and solve problems.

Attention: Concentration on learning science and solving problems.

Time management: Conducting individual learning or group work according to a schedule.

Learning environment: Being willing to study somewhere that makes it easy to concentrate or find references.

Peer learning: Collaborating with others when learning science and solving problems.

Using references: Using references for additional information.

Some strategies were designed and instructed into the instructional design, and students were required to use some strategies during their learning. For example, students were asked to summarize the important points of the contents (*Organizing*), or connect different knowledge when reading learning materials (*Elaborating*), or reading these materials repeatedly if they did not understand the contents well (*Repeating*), and these strategies were supported by the functional tools on the BookRoll system. However, not all strategies were designed or required to be used in the lessons, such as *Effort* or *Attention*. However, these STEM learning strategies were examined by the questionnaire regarding how students used these strategies during the STEM lessons.

Before the STEM lesson, students received the pre-CPS Questionnaire, and a pre-test to check their prior knowledge. After the completion of the STEM lesson, students received the same CPS Questionnaire and a new STEM Learning Strategy Questionnaire (STEM Questionnaire), which was developed by Griese et al., 2015, as post-questionnaires. The contents and items of the STEM

Questionnaire are presented in Appendix 3. The CPS post-questionnaire was conducted to assess the change in students' CPS awareness before and after the STEM lesson, while the STEM Questionnaire checked the kind of learning strategy students used during the STEM lesson, and a post-test was conducted to see whether their related knowledge had changed.

4.2.3 Data collection

To investigate possible factors affecting the development of CPS skills, the relationships between CPS awareness and learning performance, the STEM learning strategy used, and the learning behaviors in learning scientific materials during individual pre-learning and collaborative work were examined. Therefore, data were collected using four tools: questionnaires, tests, learning logs, and the dialogue during group discussion.

First, the CPS Questionnaire was used as the pre-post questionnaire. The reliability was assessed, and the overall Cronbach's α value of pre-CPS Questionnaire was 0.77 (the reliability of *Participation*, *Perspective Taking*, *Social Regulation*, *Task Regulation*, and *Learning and Knowledge Building* was 0.83, 0.79, 0.79, 0.71, 0.73 respectively), and post-CPS Questionnaire was 0.79 (the reliability of each factor same as above was 0.78, 0.84, 0.75, 0.84, 0.74 respectively).

The STEM questionnaire was used as the post-questionnaire concerning students' learning strategy during their STEM learning. The overall Cronbach's α value of STEM questionnaire was 0.78 (the reliability of *Organizing*, *Elaborating*, *Repeating*, *Effort*, *Attention*, *Time Management*, *Learning Environment*, *Peer Learning*, and *Using References* was 0.86, 0.73, 0.78, 0.71, 0.82, 0.84, 0.88, 0.70, 0.71 respectively). Both questionnaires were rated on a Likert scale from 1 to 5 (1=Strongly disagree; 2=Slightly disagree; 3=Neither; 4=Slightly agree; and 5=Strongly agree). Free text space was also provided on the post-questionnaire to collect students' individual reflections and their impressions of STEM lessons.

The pre-posttests contained the same ten questions on students' acquisition of CO_2-related knowledge. The tests included seven conceptual multiple-choice questions concerning the nature (two questions) and solubility of CO_2 (five questions), one calculation question, and two application questions that required students to solve problems related to the solubility of CO_2 and disaster reduction consciousness. Thus, the results of the tests can reflect the change of students' conceptual understanding of the CO_2-related problems and the ability to transfer their knowledge to solve the problems. The conceptual questions were the same level as their final examination, and calculation questions and application questions were more difficult than their final examination.

The learning logs of the operations students performed when reading and understanding digital learning materials through the BookRoll system were collected, yielding data on their frequency of turning to the next/previous page and adding/deleting markers, annotations. The learning logs both in-class and out-of-class were collected in this study.

Finally, the dialogues of discussion were recorded and coded to clarify how students display their CPS skills when solving problems.

4.3 Results and Discussion

4.3.1 Changes in learning performance

RQ5-a: Did the learning performance change after the STEM lessons?

The pre-post tests consist of ten questions (worth ten full marks) about knowledge related to CO_2 and disaster reduction. Due to the small sample size of the study, I looked at histograms of students' pre-posttests with the normal curve superimpose, and histograms showed not symmetric, moderate tailed distributions, which indicated apparent non-normal distributions of data. Therefore, a non-parametric Wilcoxon rank test was adopted to assess the significance of the change of pre-and post-tests concerning students' changes of related knowledge.

As shown in **Table 4**, the mean value improved from 3.42 (SD = 1.24) to 5.92 (SD = 1.51) at a significance value of 0.01, which shows statistically significant differences in students' learning performance during the STEM lesson.

In addition, according to the SD of pre-and post-tests, it is indicated that the learning performance improvement varies more in the post-test than in the pre-test. Students have acquired and constructed knowledge at different levels during the lessons, possibly related to their prior knowledge and skills. According to students' free description in the post-questionnaire, some students pointed out that they lacked "mathematical knowledge and skills for calculation," or "geography and chemistry-related knowledge." This is one possible reason why students who lack knowledge and skills benefit little during the lessons.

Table 4 Wilcoxon signed-rank test results of pre-post tests in instructional practice 5

Test	Mean	*SD*	Median	|*Z*|	*P* value
Pre-test	3.42	1.24	3.00	2.83^{**}	0.01
Post-test	5.92	1.51	6.00		

$N = 12$; $^{**}p < 0.01$

4.3.2 Changes in CPS awareness

RQ5-b: Did each factor of CPS awareness change after the STEM lessons?

As for the assessment of the pre-post questionnaires, the histograms of students' CPS pre-postquestionnaires with the normal curve superimpose were checked and found non-normal distributions of data. Therefore, a Wilcoxon signed-rank test was used to assess the significance of the change of CPS pre-postquestionnaires concerning students' awareness of whether and how to use CPS skills. The results are shown in **Table 5**.

With respect to Social Skills, Perspective Taking was increased from 13.25 (SD =2.18) to 13.67 (SD =1.37), while Participation decreased from 12.17 (SD = 2.08) to 11.92 (SD = 1.88) and Social Regulation decreased from 12.17 (SD = 2.44) to 11.58 (SD =2.19).

Concerning the Cognitive Skills, Task Regulation improved from 14.50 (SD = 3.40) to 15.08 (SD = 3.09), while Learning and Knowledge Building declined from 14.25 (SD = 2.70) to 13.75 (SD = 2.18). However, no statistically significant difference was found for any factor, indicating that CPS awareness had not improved through this STEM lesson.

The possible reason was that this STEM lesson was designed according to the CPS process (Hesse et al., 2015), including the steps of *Identifying the problem*, *Representing the problem*, *Planning and executing*, and *Monitoring and reflecting*. However, according to Hesse et al. (2015), the critical points of the latter two CPS processes are understanding other group members' states for *Identifying the problem* and understanding the group's states for *Monitoring and reflecting*. In light of these points, in earlier studies, Moodle system was used to help students and the instructor to understand mutual states. However, in the present study, I only used the BookRoll system because I focused on the effect of learning behaviors on CPS improvement.

However, it is found that the value of SD of the post-CPS Questionnaire is lower than that pre-CPS Questionnaire, which shows that the improvement of CPS awareness varies less after the lessons. Since the learning activities were designed based on the CPS processes, and all students were required to engage in the CPS activities with the group, it was indicated that students' perceptions of CPS were getting closer to each other. One possible reason was that students tended to accept others' opinions and contributions, and reach agreement during the discussion when conducting group work. In order to examine how did students conduct their CPS activities, a dialogue analysis was conducted (RQ5-f).

Table 5 Wilcoxon signed-rank test results for the CPS pre-postquestionnaires

	Factor	Mean (*SD*)		Median		|*Z*|	*P*-value
		pre	post	pre	post		
Social skills	*Participation*	12.17 (2.08)	11.92 (1.88)	12.00	11.50	0.50	0.62
	Perspective Taking	13.25 (2.18)	13.67 (1.37)	13.50	14.00	0.96	0.34
	Social Regulation	12.17 (2.44)	11.58 (2.19)	12.00	12.00	0.47	0.64
Cognitive skills	*Task Regulation*	14.50 (3.40)	15.08 (3.09)	13.50	14.00	0.82	0.41
	Learning and Knowledge Building	14.25 (2.70)	13.75 (2.18)	14.00	13.00	0.99	0.32

$N = 12$

4.3.3 Factors that influence the improvement of learning performance

RQ5-c: Which factors of STEM learning strategy and learning behaviors had relationships with the change in learning performance?

In order to investigate whether learning strategy and learning behaviors of reading scientific materials influenced learning performance, Spearman's rank correlation coefficient was used to assess the correlations between learning performance from the data of tests on the one hand and learning strategy from the SLS Questionnaire and learning logs for the reading digital learning materials on the other.

4.3.3.1 Correlations between changes in learning performance and STEM learning strategy

First, the correlations between changes in learning performance and the STEM questionnaire (see **Table 6**) were analyzed; however, no correlation was found.

Lou et al. (2011) suggest that students should be guided efficiently to immersion in STEM education. However, in this lesson, the instructor played the role of a facilitator who only controlled the flow of the lesson and provided advice or gave answers directly when necessary, indicating that efficient guidance for STEM learning is not enough in this instructional design.

As Kelley and Knowles (2016) pointed out, as an essential factor in STEM education, both educators and learners should emphasize the integration of STEM disciplines. In order to make the integrated approach more effective in conveying to students how STEM knowledge can be applied to real-world problems, it is necessary for students to think and understand the relevant ideas in the individual disciplines and multidisciplinary integration (Kelley & Knowles, 2016). However, the results of the students' free text questionnaire suggest that they only focused on scientific or mathematical knowledge and on how to use it to solve a specific provided problem, rather than thinking of relevant ideas or integration. This is one possible reason why students' STEM learning strategy failed to help them to improve their learning performance.

Table 6 Spearman's rank correlation coefficients between learning performance and STEM learning strategy

	Learning performance			
STEM Learning Strategy	*Organizing*	−0.79 (0.10)	*Time Management*	−0.44 (0.15)
	Elaborating	−0.49 (0.10)	*Learning Environment*	0.00 (0.10)
	Repeating	0.03 (0.93)	*Peer Learning*	−0.09 (0.78)
	Effort	0.07 (0.83)	*Using References*	−0.47 (0.13)
	Attention	0.14 (0.66)		

$N = 12$; ρ(Sig.)

4.3.3.2 Correlations between changes in learning performance and learning behaviors

Regarding the correlations between changes in learning performance and the learning behaviors involved in reading digital learning materials, learning behaviors were divided into two parts, pre-learning, and group discussion. The results are presented in **Table 7**.

During pre-learning, there was no correlation between changes in learning performance and learning behaviors, and the same reason was considered to be involved here as above, the lack of understanding and thinking about STEM learning methods, as well as guidance from instructors in STEM learning.

Turning to learning behaviors in group discussion, this included students' operations when reading digital learning materials. Some functional tools such as markers and annotations indicate behaviors associated with students' thinking (for example, highlighting when they do not understand) and changes in their thinking (deleting markers when they change an idea). The results in **Table 7** show that there was a moderate positive correlation between changes in learning performance and *Add Marker* ($\rho = 0.66$, $p < 0.05$), and a strong positive correlation between changes in learning performance and *Delete Marker* ($\rho = 0.76$, $p < 0.01$).

Students frequently add or delete their markers during group discussions because they take others' contributions into mind when reconsidering problems, which was also confirmed by our classroom observation. The marker tool is effective in facilitating students' deeper processing and retrieval if instruction in thinking about what to mark and in questioning when re-reading is provided (Yue, Storm, Kornell, &Bjork, 2015); otherwise, it may negatively affect performance on higher-level tasks that require them to make inferences (Dunlosky, Rawson, Marsh, Nathan, &Willingham, 2013).

In this STEM instructional design, students were required to highlight the context they did not understand in yellow and the important contexts in red before the lesson and discuss these contexts during the lesson. They were also asked to delete the markers if they change their ideas after the discussion. Since no correlation between changes in learning performance with marker-using behaviors was found during pre-learning but was found during group discussion, it can be inferred that marker-using behaviors could facilitate the integration of other contributions into their own thoughts and reconsidering the problems (*Perspective Taking*). However, I have no observations supporting this. Thus, the dialogue analysis had been conducted to examine whether students had the behaviors of perspective taking during discussion.

Table 7 Spearman's rank correlation coefficients between learning performance and learning behaviors

	Learning Performance			
	Pre-learning		**Group discussion**	
Learning behaviors	Next(p)	−0.26 (0.41)	Next(g)	0.46 (0.13)
	Prev(p)	−0.08 (0.80)	Prev(g)	0.27 (0.40)
	AM(p)	−0.27 (0.39)	AM(g)	0.66^{*} (0.02)
	DM(p)	−0.31 (0.33)	DM(g)	0.76^{**} (0.00)
	AA(p)	−0.34 (0.28)	AA(g)	0.32 (0.31)
	AB(p)	0.26 (0.43)	AB(g)	0.42 (0.18)

ρ(Sig.); $N = 12$; $^{**}p < 0.01$, $^{*}p < 0.05$

Note: Next (*Next*); Prev (*Previous*); AM (*Add Marker*); DM (*Delete Marker*); AA (*Add Memo[annotation]*); AB (*Add Bookmark*)

(I have also collected the logs of *Delete Annotation* and *Delete Bookmark*; however, the data was 0.)

(p): During the pre-learning; (g): During the group discussion.

4.3.4 Factors influence the improvement of CPS awareness

RQ5-d: Which factors of STEM learning strategy and learning behaviors had relationships with the change in CPS awareness?

In order to determine factors that might affect the improvement of CPS skills, Spearman's rank correlation coefficient was used to assess the correlations of CPS awareness from the data of CPS Questionnaires with STEM learning strategy (STEM Questionnaire) and learning logs (reading digital learning materials).

4.3.4.1 Correlations between changes in CPS awareness and STEM learning strategy

From the results in **Table 8**, there were strong negative correlations of *Social Regulation* in CPS awareness with *Organizing* ($\rho = -0.74$, $p < 0.01$) and *Using References* ($\rho = -0.77$, $p < 0.01$) in STEM learning strategy.

Since *Social Regulation* refers to strategies recognizing the diversity of group members and negotiating with them, the point of this factor is communication with others. When conducting STEM education, it is necessary for STEM educators to provide students with multidisciplinary, multi-perspective viewpoints and a collaborative approach that links them with a broader community (Kelley & Knowles, 2016; Kennedy & Odell, 2014). However, the STEM learning strategies in this study focused on individual learning (except in the case of *Peer Learning*) and found that individual STEM learning strategy negatively affected communication during group work. Furthermore, no training or guidance was provided on how to learn integrated STEM subjects, so future research should consider how to guide students to master STEM learning well and integrate individual learning strategies, especially these four factors, efficiently into collaboration.

Table 8 Spearman's rank correlation coefficients between CPS awareness and STEM learning strategy

		CPS awareness				
		Social skills			Cognitive skills	
		Participation	*Perspective Taking*	*Social Regulation*	*Task Regulation*	*Learning and Knowledge Building*
STEM Learning Strategy	*Organizing*	0.08 (0.81)	0.20 (0.53)	−0.74** (0.01)	−0.13 (0.70)	0.09 (0.79)
	Elaborating	0.39 (0.21)	0.08 (0.80)	−0.50 (0.10)	0.24 (0.46)	−0.02 (0.95)
	Repeating	0.22 (0.49)	−0.16 (0.62)	−0.05 (0.89)	−0.12 (0.70)	0.08 (0.82)
	Effort	0.21 (0.52)	−0.25 (0.44)	−0.14 (0.67)	−0.35 (0.27)	0.13 (0.68)
	Attention	0.30 (0.34)	0.31 (0.33)	0.21 (0.51)	-0.09 (0.79)	-0.18 (0.57)
	Time Management	0.16 (0.61)	−0.15 (0.65)	−0.52 (0.09)	−0.18 (0.58)	−0.32 (0.32)
	Learning	0.17	−0.06	−0.25	0.19	−0.10

	Environment	(0.59)	(0.85)	(0.43)	(0.56)	(0.77)
	Peer Learning	−0.23 (0.47)	−0.29 (0.36)	−0.38 (0.22)	0.44 (0.15)	−0.38 (0.23)
	Using References	−0.08 (0.80)	−0.04 (0.91)	-0.77^{**} (0.00)	−0.23 (0.46)	−0.10 (0.77)

ρ(Sig.); $N = 12$; $^{**}p < 0.01$

4.3.4.2 Correlations between changes in CPS awareness and learning behaviors

Next, the correlations were assessed between CPS awareness and learning behaviors concerning how students read digital STEM learning materials. The results are presented in **Table 9**.

During pre-learning, moderate negative correlations were found for *Learning and Knowledge Building* in CPS awareness with *Add Marker* ($\rho = -0.60$, $p < 0.05$) of learning behaviors.

In an earlier study, I concluded that students' behaviors of frequently changing pages or turning to the previous page imply a lack of familiarity with the learning contents and cause them difficulties in constructing knowledge. They added markers to what they thought was important or thought they understood and deleted markers when they changed ideas, from which it could also be inferred that they understood the contents poorly and thus changed their minds easily. However, the Add Marker logs collected included both yellow (not understand) and red (important) highlights, meaning that it was difficult to identify which part of their behaviors negatively affected their knowledge building.

In group discussions in STEM lessons, there were moderate positive correlations found between *Social Regulation* in CPS awareness and *Add Marker* ($\rho = 0.60$, $p < 0.05$) and *Delete Marker* ($\rho = 0.64$, $p < 0.05$) of learning behaviors.

During group discussion, I observed that when students discussed the problems and the contents they did not understand, they deleted the old markers when they accepted others' opinions while adding new markers. Therefore, the behaviors of adding and deleting markers indicate they paid attention to communication and negotiation in group work, showing that the effective utilization of the marker tool could facilitate social regulation in STEM lessons. Furthermore, students' behaviors of social regulation during discussion would be examined by dialogue analysis.

Table 9 Spearman's rank correlation coefficients between CPS awareness and learning behaviors

		CPS awareness				
		Social skills			Cognitive skills	
		Participation	*Perspective Taking*	*Social Regulation*	*Task Regulation*	*Learning and Knowledge Building*
Learning Behaviors	**Pre-learning**					
	Next(p)	−0.00 (0.99)	0.44 (0.15)	−0.33 (0.29)	0.31 (0.33)	−0.47 (0.13)
	Prev(p)	0.40 (0.19)	0.40 (0.20)	0.08 (0.82)	0.08 (0.80)	−0.55 (0.07)
	AM(p)	0.22 (0.50)	0.41 (0.18)	−0.10 (0.76)	0.25 (0.44)	-0.60^{*} (0.04)
	DM(p)	−0.04 (0.92)	0.24 (0.45)	−0.29 (0.36)	0.31 (0.33)	−0.54 (0.07)
	AA(p)	0.00 (1.00)	0.20 (0.54)	−0.25 (0.43)	−0.10 (0.75)	−0.50 (0.10)
	AB(p)	0.25 (0.43)	0.00 (1.00)	0.08 (0.80)	−0.13 (0.69)	−0.03 (0.93)
	Group discussion					
	Next(g)	−0.03 (0.92)	−0.06 (0.86)	0.11 (0.74)	−0.45 (0.14)	0.39 (0.21)
	Prev(g)	−0.08 (0.80)	−0.29 (0.35)	0.18 (0.58)	−0.41 (0.19)	0.20 (0.54)
	AM(g)	0.27 (0.40)	−0.01 (0.97)	0.60^{*} (0.04)	0.15 (0.65)	0.17 (0.59)
	DM(g)	0.05 (0.89)	−0.22 (0.50)	0.64^{*} (0.03)	0.06 (0.85)	0.24 (0.46)
	AA(g)	0.49 (0.10)	0.00 (1.00)	0.26 (0.41)	0.40 (0.20)	0.13 (0.68)
	AB(g)	0.45 (0.15)	0.10 (0.76)	0.40 (0.20)	0.35 (0.27)	−0.09 (0.79)

ρ(Sig.); $N = 12$; $^{*}p < 0.05$

4.3.5 Relationships between learning strategies and learning behaviors

RQ5-e: What were the relationships between STEM learning strategy and learning behaviors in STEM learning?

In this study, questionnaires were used to investigate how students used STEM learning strategies but did not provide instruction or guidance in using STEM learning strategies efficiently. Therefore, the correlations between STEM learning strategy and learning behaviors of reading scientific materials were assessed to find out how their learning strategy affected their actual learning behaviors, which could help the future instructional design in ways of using STEM learning strategy. According to the results in **Table 10**, in students' pre-learning, no significant correlation was found between STEM learning strategy and learning behaviors at the significant level of $p < 0.05$.

As for the group work, moderate positive correlations were shown between *Repeating* of STEM learning strategy and *Previous* ($\rho = 0.61$, $p < 0.05$) of learning behavior, and a strong positive correlation between *Effort* and Previous behavior ($\rho = 0.75$, $p < 0.01$). On the other hand, there was a moderate negative correlation found for *Organizing* strategy with *Add Marker* behavior ($\rho = -0.58$, $p < 0.05$), and a strong negative correlation between *Organizing* strategy and *Delete Marker* behavior ($\rho = -0.74$, $p < 0.01$). Besides guidance on how to use the functional tools of the BookRoll system, some learning strategies such as organizing/summarizing, elaborating/application and repeating should also be taught with efficient design under certain learning conditions (Dunlosky et al., 2013).

Table 10 Spearman's rank correlation coefficients between STEM learning strategy and learning behaviors

		Learning Behaviors					
		Pre-learning					
		Next(p)	Prev(p)	AM(p)	DM(p)	AA(p)	AB(p)
STEM Learning Strategy	*Organizing*	0.31 (0.32)	0.08 (0.79)	0.22 (0.50)	0.30 (0.35)	0.26 (0.42)	0.08 (0.81)
	Elaborating	0.18 (0.59)	0.05 (0.89)	0.15 (0.65)	0.25 (0.25)	0.18 (0.57)	-0.03 (0.92)
	Repeating	−0.25 (0.43)	−0.05 (0.88)	-0.28 (0.38)	−0.26 (0.42)	−0.09 (0.79)	0.37 (0.24)
	Effort	−0.43 (0.16)	−0.16 (0.61)	−0.44 (0.15)	−0.47 (0.13)	−0.21 (0.51)	0.24 (0.46)
	Attention	0.05 (0.88)	0.43 (0.16)	0.33 (0.29)	0.15 (0.65)	0.54 (0.07)	0.06 (0.85)
	Time	0.03	0.27	0.23	0.17	0.40	0.17

	Management	(0.92)	(0.39)	(0.48)	(0.60)	(0.20)	(0.60)
	Learning Environment	−0.42 (0.17)	−0.43 (0.16)	−0.54 (0.07)	−0.52 (0.09)	−0.51 (0.09)	−0.18 (0.57)
	Peer Learning	0.02 (0.96)	−0.18 (0.58)	−0.13 (0.69)	0.07 (0.84)	-0.10 (0.75)	0.02 (0.95)
	Using References	−0.00 (1.00)	−0.11 (0.74)	−0.11 (0.73)	0.02 (0.96)	0.24 (0.46)	0.09 (0.78)
		Group discussion					
		Next(g)	Prev(g)	AM(g)	DM(g)	AA(g)	AB(g)
STEM Learning Strategy	*Organizing*	−0.25 (0.43)	−0.29 (0.37)	-0.58^{*} (0.05)	-0.74^{**} (0.01)	−0.09 (0.78)	−0.22 (0.49)
	Elaborating	−0.26 (0.42)	−0.29 (0.37)	−0.41 (0.19)	−0.55 (0.06)	0.45 (0.15)	−0.05 (0.87)
	Repeating	0.51 (0.09)	0.61^{*} (0.03)	0.24 (0.45)	0.19 (0.55)	0.31 (0.32)	0.46 (0.32)
	Effort	0.56 (0.06)	0.75^{**} (0.01)	0.28 (0.39)	0.24 (0.45)	0.18 (0.58)	0.39 (0.21)
	Attention	0.34 (0.28)	0.24 (0.28)	0.27 (0.39)	0.157 (0.63)	0.09 (0.78)	0.03 (0.94)
	Time Management	−0.20 (0.53)	0.12 (0.72)	−0.33 (0.30)	−0.44 (0.16)	-0.14 (0.67)	0.08 (0.79)
	Learning Environment	0.19 (0.56)	0.42 (0.17)	0.32 (0.32)	0.25 (0.43)	0.36 (0.25)	0.58 (0.05)
	Peer Learning	−0.04 (0.91)	0.25 (0.43)	0.02 (0.95)	0.02 (0.96)	0.13 (0.68)	0.26 (0.42)
	Using References	0.17 (0.61)	0.09 (0.77)	−0.42 (0.18)	−0.43 (0.17)	0.09 (0.77)	0.05 (0.87)

ρ(Sig.); $N = 12$; $^{**}p < 0.01$, $^{*}p < 0.05$

4.3.6 Differences in high and low learning performers

RQ5-f: Between high and low learning performers, what was the difference in strategic and behavioral factors that influence learning performance and CPS awareness?

In order to explore whether and how would students' individual cognitive differences affect their development of new knowledge and CPS awareness, we divided the students into two groups, high-performance and low-performance groups, according to their pre-test scores, and examined the differences in the changes of CPS awareness, and the different factors that affect learning performance and CPS awareness. The students who gained a pre-test score in the top 25 percentile (first quartile) were categorized into the high-performance group (N = 2, Mean = 5.5), and those who gained a pre-test score in the bottom 25 percentile (third quartile) were classified as the low-performance group (N = 3, Mean = 2).

First, the results indicated no difference in factors of CPS awareness, learning behaviors, and STEM learning strategy between the high and low performers. However, since there are only two students in the high-performance group, the correlation between the factors is either 1 or -1, making it difficult to compare the result with the low-performance group.

From the results above, it is hard to draw a conclusion regarding the effect of prior knowledge on the learning effectiveness during the lessons in this instructional practice.

4.3.7 Dialogue analysis

RQ5-g: How did students display CPS skills during the discussion?

The Spearman's rank correlation coefficient revealed significant positive correlations between the utilization of marker tool with changes in learning performance and CPS *Social Regulation* awareness during the group discussion. In order to investigate whether students had the behaviors of *Social Regulation*, a dialogue analysis was conducted to understand how students displayed these skills.

The dialogue data of all groups during the discussion were collected and categorized dialogue thread in relation to *Social Regulation* with reference to the Hesse et al. (2015). According to the CPS framework proposed by Hesse et al. (2015), there are four elements in *Social Regulation*, which are negotiation, self-evaluation (meta-memory), transactive memory, and responsibility initiative. The elements and the indicators of *Social Regulation* were listed in **Table 11**.

Table 11 Elements and indicators in *Social Regulation* factor

CPS skill	Element	Indicator
Perspective taking	**Adaptive responsiveness**	Accepting or adapting the contributions of others
	Audience awareness	Awareness of how to adapt behavior to increase suitability for others
Social regulation	**Negotiation**	Achieving a resolution or reaching a compromise
	Self-evaluation	Recognizing own strengths and weaknesses
	Transactive memory	Recognizing the strengths and weaknesses of others
	Responsibility initiative	Assuming responsibility for ensuring parts of the task is completed by the group

***Perspective taking*—Adaptive responsiveness**

Example 1

95. Student 9 (S9): The change of the temperature has increased.
96. S7: You mean the temperature has increased?
97. S9: Because there is a difference in the temperature (between two places).
98. S7: Yeah, yeah, yeah, I got it.
99. S9: In the lake.
100. S7: So difficult to accumulate (CO_2)?
101. S9: Because water constantly circulates through.
102. S7: Yes, yes, yes.

…

118. S10: So back to the question, what about in Japan?
119. S9: See the beginning of this chapter (of the learning materials on the BookRoll system). There is a huge feature in Cameroon, which is a landslide. Especially in summer, it rains almost every day.
120. S10: Yeah, yeah, yeah.
121. S9: Landslides occur easily (in Cameroon), but landslides don't often occur in Japan.
122. S10: Yes, that's true.

Adaptive responsiveness includes the indicator "ignoring, accepting, or adapting contributions of others.” As shown in example 1, in Line 98, S7 used “I got it” to express his agreement with S9’s explanations, which means he has accepted other’s viewpoints and reconsidered the problems (in Line 100). Similarly, in Line 122, S10 used “Yes, that’s true” to show his agreement with S9’s viewpoint. Since S9 provided his explanations based on the learning materials on the BookRoll system (in Line 119), it could be inferred that the S9 did have the behaviors of Adaptive responsiveness during the utilization of the BookRoll system, which is consistent with the findings of relationships between marker tool utilization with changes in learning performance.

***Perspective taking*—audience awareness (mutual modeling)**

Example 2

63. S4: Is Japan different from Cameroon?
64. S5: Of course, different, like precipitation.
65. S6: Completely different.
66. S5: Look at this (the learning materials on the BookRoll system), this is different from this, but in summer, precipitation is not that different.
67. S4: Yeah, I see.
68. S6: Because Japan’s temperature is similar to Cameroon’s? Like June.
69. S4: That’s true.

…

76. S6: As for Cameroon, where is its location? Around the sea?
77. S5: No, it isn’t. (Searching the information on the Internet). Here.
78. S4: Yeah, that’s the point. The locations are different.
79. S5: And there is information on Cameroons’ temperature here.
80. S4: Is Cameroon above the equator?
81. S6: About the location, look at the first page (of the learning materials).
82. S7: Yeah, I see. I think we should work on the problem now.

According to the CPS framework, the indicator of Audience awareness is “awareness of how to adapt behavior to increase suitability for others.” In Example 2, when others had difficulties understanding specific contents, some students used additional references or information to explain the contents.

For example, in Lines 64 and 65, S5 and S6 answered S4’s question but did not receive any feedback, which means S4 did not accept their answers well. So S5 waited for 3 s and chose to use learning materials to explain the question (in Line 66). Moreover, he also searched for additional information for S6’s question (in Line 77). It is indicated that he had adapted his own behavior based on the feedback and understanding of the recipient.

Based on their behaviors of providing additional information by the BookRoll system (for example, in Line 66, 81), it can be inferred that students utilized BookRoll system tools with their audience awareness.

***Social regulation*—negotiation**

Example 3

25. S2: Usually, the water in that lake, doesn't circulate.

26. S1: I think it does.

27. S2: No, it doesn't.

28. S1: Why?

29. S2: The precipitation is high.

30. S1: That's why I think it circulates. Because even the precipitation is low, the water would circulate in the lake. I understand what you are talking about, but it is strange that the water doesn't circulate, even the precipitation is high.

This example showed a negotiation during the group discussion around the "whether water circulates in the lake" issue. Negotiation was conducted here in order to "reaching a compromise." In Line 25~27, S1 and S2 expressed their opinions, respectively. After that, S2 asked the reasons (in Line 28), commented on the difference between their viewpoints, and proposed reasons, to persuade S2 to achieve the agreement (in Line 30).

Although students' negotiation behaviors were found during CPS learning, it was not clarified whether their negotiation behaviors had a relationship with the use of BookRoll tools.

***Social regulation*—Self-evaluation**

Example 4

10. S1: (Searching the information on the Internet) What about Cameroon…There is only the English version, I'm finished.

…

17. S1: It is too terrible.

18: S3: About what?

19. S1: My English.

The Self-evaluation behavior had not been executed often and was found in only one group about the evaluation on his English ability.

***Social regulation*—Transactive memory**

There was no Transactive memory behavior found in all groups.

***Social regulation*—Responsibility initiative**

10. S1: (Searching the information on the Internet) What about Cameroon…There is only the English version, I'm finished.

11. S1: (Reading out the contexts on the BookRoll system.) Yes, I agree.

12. S2: How dangerous would it be? The limnic eruption.

13. S1: It has been written here.

…

46. S2: What about searching on the Internet?

47. S3: Good idea.

48. S1: I will search for the history of Cameroon on Wikipedia.

The indicator of Responsibility initiative is "assuming responsibility for ensuring parts of the task are completed by the group," such as conducting activities and reporting to others, assuming group responsibility as one's own responsibility. In Line 11 and 13, S1 had investigated certain information and reported it to other members. And in Line 46 and 48, S2 had proposed the activities which group members should conduct. S1 accepted that responsibility and taken it as his own responsibility. Moreover, the Responsibility initiative behavior was found during the use of the BookRoll system (in Line 11), which was consistent with the relationship found between marker tool use and CPS social regulation.

4.4 Conclusion

In this experiment, CPS-based STEM lessons were designed by integrated with STEM learning strategy. The effectiveness of the practical experiments was examined from two aspects, the CPS design, and the STEM learning outcomes. The results of this instructional practice are presented in Figure 10.

Regarding the effectiveness of CPS design, the improvement of CPS awareness was examined. However, no significant change was found in CPS awareness after the STEM lessons. When examining the correlations between changes in CPS awareness and STEM learning strategy, some factors of STEM learning strategy, including *Organizing* and *Using References*, showed negative correlations with *Social Regulation* of CPS social skills. Moreover, negative correlations were also found between *Learning and Knowledge Building* of CPS cognitive skills and *Add Marker* behavior in students' pre-learning. These results imply a deficiency in and a necessity for efficiently guiding students in using STEM learning strategies or functional tools and integrating them into collaborative activities. The positive correlations found for *Add and Delete Marker* in group discussions with *Social Regulation* of CPS social skills also indicate the effectiveness of marker tools.

Regarding the STEM learning outcomes, the aim was to acquire related knowledge and apply the knowledge to authentic problem-solving. The outcomes concerning this aim were assessed through the final presentations, tests, and dialogue analysis. First, students acquired and constructed related knowledge through the lectures and group discussion and solved problems by reaching an agreement within the groups. The teachers assessed all the groups' solutions during the presentations and revised the knowledge by pointing out the discrepancies between the final solution and their reasons. Here is one example of the correct answer in the presentation. Some groups judged that the same Limnic Eruption disaster would not occur in Japan. They explained that the annual temperatures in the two countries were not the same, and different from Cameroon, there were four seasons in Japan, which would cause the lake circulation and avoid the accumulation of the CO_2. In these groups, the manual of disaster mitigation they created included the measurements for the Limnic Eruption disaster in Cameroon and related with other unavoidable natural disasters in Japan. In these groups, students gave the example of the earthquake and volcanic eruption that occurred in Japan and explained the disaster mitigation when facing such disasters. However, they only knew that the mechanisms of these disasters were different from the Limnic Eruption but not understood the exact mechanisms of these disasters. Due to the limited time of the lessons and considering the main aim of the lessons, the teacher did not explain the mechanisms of other disasters in class but provided the related references to students through Moodle system.

Second, pre-post tests were conducted to examine the acquisition and application of the related knowledge. It was found that the learning performance was significantly improved after the STEM lessons. In order to identify what factors of STEM learning strategy, and learning behaviors would affect learning performance and improve the instructional design, the correlations between learning performance, STEM learning strategy and learning behaviors were examined. Some critical factors were identified, and these factors should be considered on different occasions. For example, it is better to use STEM strategies such as *Organizing* and *Elaborating* in individual learning and using the marker tool positively in group work. In addition, the frequency of Add and Delete Marker behaviors in group discussion showed a positive influence on students' learning performance. Since I only analyzed the correlations between certain variables, it can also be inferred that students whose learning performance improved more showed a tendency to use marker tools more frequently. Both explanations indicate that marker tools can be used effectively in STEM learning performance improvement. Furthermore, to determine how to support students in utilizing their STEM learning strategy, the correlations between students' STEM learning strategy and their actual learning behaviors were assessed. In the group discussion, there were positive correlations between *Repeating* and *Effort* strategies and *Previous* behaviors, while negative correlations were found for the *Organizing* strategy with *Add and Delete Marker* behaviors. These results suggest the value of teaching these strategies using functional tools.

Finally, to examine how students used their CPS skills to construct knowledge, students' utterances and actions during the group work were analyzed by the dialogue analysis. In this instructional practice, the use of *Social Regulation* skills, which were positively related to the behaviors during group work, were identified during the group discussion. The results indicate that the *Social Regulation* skills are effective during group discussion including negotiating with each other to reach an agreement, recognizing one's own strengths and weaknesses related to the metacognition, and assuming responsibility to ensure completion of the task.

Based on the results above, some implications are indicated. First, when participating in collaborative activities in STEM learning, the marker tool is considered effective in STEM learning performance improvement because of its advantages, such as helping students focus on the discussion topic and integrating contributions from others into their own thoughts.

Second, certain factors in STEM learning strategy should be executed by an individual, such as organizing and using reference. Besides, it is also suggested that the marker tool is helpful in students' group work, including communication and negotiation.

Third, although the marker tool is shown to be helpful in collaborative activities, it does not help students in knowledge building and knowledge organizing without detailed guidance about how to utilize such a tool.

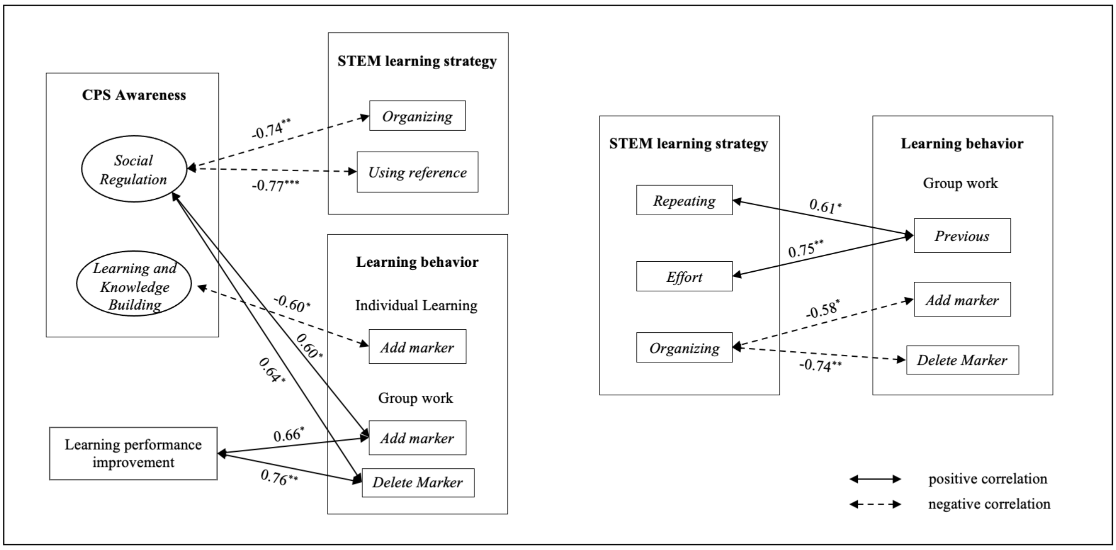


Figure 10. The results of Instructional practice 5

4.5 Limitations and future work

The first limitation of this experiment is the small number of participants, which makes the results hard to generalize. In future work, the sample size should be increased to gain a more generalizable conclusion and provide specific implications for CPS-based STEM design.

Second, as many results in the present study indicate, it is vital to provide students with training or guidance in applying STEM learning strategies and functional tools, especially marker and annotation tools, which should also be considered in future work.

Finally, from the above results, we can only see the mutual relationships among the use of STEM strategy, learning behaviors, CPS awareness, and learning performance. In order to construct a practical CPS process framework, it is necessary to clarify the causal relationships among these factors, find out what factors might affect the improvement of CPS awareness, and finally improve the learning performance.

Chapter 5: Instructional Practice for Designing Collaborative Problem Solving Process Framework in STEM Education

5.1 The aim of instructional practice 6

In instructional practice 5, a CPS-based STEM course was designed, and its effectiveness was assessed. The relationships between different factors were examined to clarify the potential factors that influence the improvement of learning performance and CPS awareness. Moreover, the discussion was analyzed to clarify how students used their CPS skills to solve problems. However, some challenges still remain, as I discussed in Chapter 4.

First, regarding the small sample size and the insufficient time and guidance for students, in this experiment, CPS-based STEM lessons were designed, with a longer experiment duration, larger sample size, to ensure the quality of using STEM learning strategy and functional tools. The instructions for using STEM learning strategy and functional tools were designed based on the results of instructional practice 5 and adjusted according to the different learning phases.

This design aims to confirm the effectiveness of the CPS-based STEM course, which was designed based on the CPS processes and integration of STEM. The design also examines the causal relationships between students' use of STEM learning strategies, learning behaviors, CPS awareness, and learning performance, to identify the important factors that should be considered in CPS-based STEM design. To examine the causal relationships with learning effectiveness, in instructional practices 1~5, the mutual relationships between related factors were examined first, and the important factors that might affect learning effectiveness were selected. Similar to instructional practice 5, the aims of designing and assessing this instructional practice include two aspects, the effectiveness of CPS design and the outcomes of STEM lessons. First, regarding the CPS design, the aim of four instructional practices was to improve students' CPS skills. Second, concerning the outcomes of STEM lessons, the aim of this instructional practice was to acquire related knowledge and apply the knowledge to authentic problem solving.

For this purpose, the following research questions were proposed:

RQ6-a: Did the learning performance change after the STEM lessons?

RQ6-b: Did each factor of CPS awareness change after the STEM lessons?

RQ6-c: What were the effects of students' learning behaviors, changes in the use of STEM learning strategies, and changes in CPS awareness on the improvement of learning performance?

In addition, considering students' learning progress, the whole STEM course was divided into three phases according to the learning contents and students' learning experience. Since different teaching methods and instructions were conducted during three phases, this study aimed to collect and analyze students' learning behaviors in different phases and to find out what factors would affect learning performance in different conditions. Moreover, to provide appropriate instructions regarding what strategies were effective and how to use them effectively, effective learning strategies were identified by connecting these behaviors with specific learning strategies.

RQ6-d: What were the effects of students' learning behaviors on the improvement of learning performance in different learning phases?

In this practice, students were asked to preview the learning materials in advance and after the lessons, as their individual learning behaviors. When conducting group discussion, students were also required to use the knowledge in learning materials and to solve the problems, as their group learning behaviors. Since the activities in in-class and out-of-class learning were designed based on the differences CPS processes (Hesse et al., 2015), it was necessary to understand the different effects of learning behaviors on the improvement of learning performance and CPS awareness in different activities.

RQ6-e: What factors of learning behavior affected the improvement of learning performance and CPS awareness during in-class and out-of-class learning?

As the individual cognitive differences would affect students' acquisition of new knowledge (Dinsmore et al., 2014), the difference between high performers and low performers was examined, regarding the learning effectiveness.

RQ6-f: Between high and low learning performers, what was the difference in strategic and behavioral factors that influence learning performance and CPS awareness?

To assess students' CPS skills during CPS-based STEM lessons, the dialogue analysis was conducted to analyze students' discussion during CPS activities.

RQ6-g: How did students display CPS skills during the discussion?

5.2 Methods

5.2.1 Context

According to the teaching schedule of the experimental school, the theme of the course was set as "Solutions around us," including sub-themes of (a) *The Formation of Solutions*, (b) *Various Types of Solutions*, and (c) *Using Solutions Safely*. Based on the related content and scientific knowledge, an additional sub-theme, (d) *Limnic Eruption*, was added to this course and revised according to students' proficiency levels. The final goal of each sub-theme was to propose the solutions based on the explanation for the problems and to reach an agreement within the group. For example, in the "The Use of Acid-Base Solutions" issue, students need to find examples of the use of neutralization after recognizing acidic and basic substances by groups. In the "Acid Rain" issue, in order to judge the truth of news on the Internet, students need to analyze the elements of the news and judge whether these elements are correct by groups. In the topic of "Limnic Eruption," as in instructional practices 2, 4, and 5, students need to propose a disaster mitigation manual based on the agreement of the group. Students were divided into small groups (three~four students per group) according to their seats or student numbers, to minimize the heterogeneity of the group composition. One part of the learning materials for each topic is presented in Figure 11.

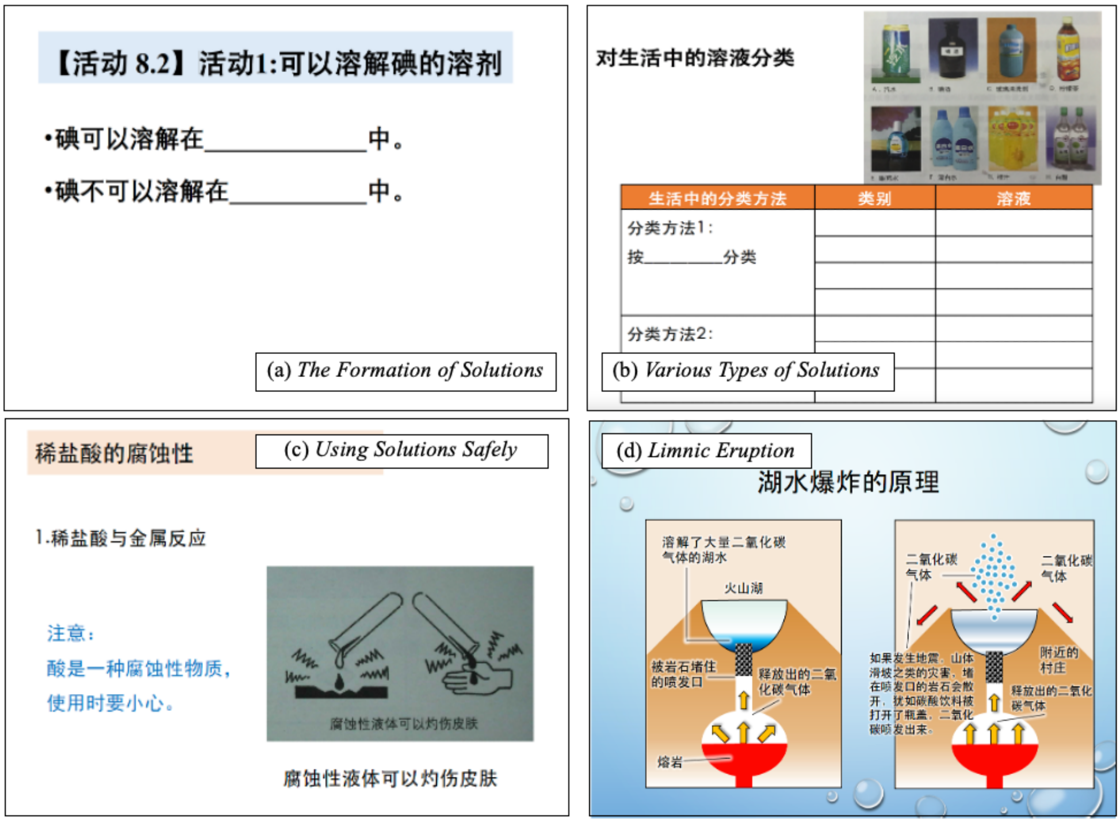


Figure 11. A part of the learning materials for each topic in instructional practice 6

Each group was required to make a presentation as the final product of CPS learning. In the first topic, (a) *The Formation of Solutions*, students were required to find examples of solutions and describe the solute and solvent in the presentation. The teacher commented on whether their examples were correct. In the second topic, (b) *Various Types of Solutions*, students were required to provide examples of applying acid-base neutralization in daily life in the presentation. The teacher commented on whether their examples were correct. In the third topic, (c) *Using Solutions Safely*, students were required to judge whether the news on the Internet regarding acid rain was true or false and provide the reasons for their judgments. In this topic, the answers could be judged as correct as long as the reasons students provided were reasonable and consistent with the answers. If they judged the news was false, they should indicate the specific wrong information in the news. For example, the pH of the rain was not below 5.6, or the phenomenon of acid rain did not occur at that time. In the final topic, (d) *Limnic Eruption*, the requirement and criteria of the assessment for students' presentations were the same as instructional practice 5.

Four STEM domains were integrated into this course. First, regarding the science domain, students learned scientific knowledge about solutions, such as the formation, characteristics, application of solutions, and the skills to solve problems in real life. Second, as for the technology domain, students were required to use functional tools on the *BookRoll* system to conduct their online reading and learning and to use the *Moodle* system to help students manage their learning information and share information with others. In addition, students were asked to utilize the Internet to search for information related to the problems they needed to solve. Third, regarding the engineering domain, students were asked to integrate the knowledge and information they learned, and design some solutions or plans for the related problems. Finally, the mathematics domain concerned certain mathematics knowledge regarding solubility and acidity-basicity (pH value), and mathematical thinking when solving problems, such as evaluating the solutions or plans students designed and implementing reasoning when solving problems. The purpose of the lessons was to understand the scientific knowledge related to CO_2 and reflect on the implications for the environment and human beings by designing the disaster mitigation manual.

5.2.2 Procedure

This study was conducted in a seventh-grade science class at a private junior high school in Shanghai, China, originally with the participation of 114 students aged 14–15 years old. The students came from four classes but were allocated the same science teacher. The situations of the experiment school are described regarding the following two aspects, the STEM teaching and learning experience and the use of technology. First, students started their multidisciplinary science course (containing chemistry, physics, biology, and geography as separate chapters) from seventh grade in Shanghai. The learning materials and the curriculum outline of this multidisciplinary science course are unified in Shanghai. However, in this science course, science-related disciplines are set separately, and it is difficult for students to integrate these disciplines. Therefore, it was considered important to integrate the important factors of STEM education into their science course. Moreover, in junior high school, problems in science lessons are always well-defined, and students have few chances to understand scientific facts and acquire procedural knowledge through solving ill-defined problems. Second, the science teacher in this school is an experienced teacher who prefers traditional lectures with the use of paper textbooks and blackboards and hardly uses technology in the science lessons. Therefore, although students had computer lessons every week, it was the first time to use computers in their science lessons. Therefore, when the systems including BookRoll and Moodle system were used in this instructional practice to support students' cognitive and collaborative activities, the guidance and practice time were provided to students in longer duration than other practices.

Before the lessons, students received CPS and STEM Questionnaires as pre-questionnaires and a pre-test to check their prior knowledge regarding the lessons they were about to learn. After the completion of each theme, students took a post-test regarding the current theme. After the whole lessons, students received the same CPS and STEM Questionnaires as post-questionnaires. Due to the absence of some students, and data missing from the questionnaires, final data from 106 students were collected. Among these participants, 50 were male (47.2%) and 56 were female (52.8%).

The activities in the first week were designed to familiarize students with the system and learning strategies. Thus, the data collected during this week were not included in the data analysis and results. From the second to the fourth week, students took their CPS-based STEM lessons with one theme per week. After each weekly lesson, students took a comprehension test to check the changes in the learning performance. After the entire course, students were required to take the same CPS and STEM Questionnaires as their post-questionnaires. The design of the CPS process was the same as instructional practice 5. Students were divided into different groups randomly, and each group contained 3~4 students. However, the whole STEM course was divided into three phases, *Learning and practice*, *Reinforcement*, *Application*, according to the learning contents and students' learning experience.

Phase 1: *Learning and practice*. The goal of this phase was to ensure the students acquired basic new knowledge and skills. This phase also included instructions for basic STEM learning strategies, such as organizing the important points of the contents, connecting new scientific facts with earlier ones, or practical applications.

Phase 2: *Reinforcement*. The goal of this phase was to enhance the students' understanding of prior and newly acquired knowledge and skills. The learning forms and activities were conducted and revised based on the results of Phase 1, and the knowledge and contents were related but more complicated than Phase 1. The STEM learning strategies were also emphasized.

Phase 3: *Application*. The main goal in this phase was to activate prior knowledge and skills, supplement new knowledge and skills according to the problems provided in real situations, and connect this knowledge and skills to solve the problems. Students were provided a new topic related to a natural disaster in the real world in this phase. To solve the related problem, it was necessary to use not only the knowledge in the textbook but also some practical experience and supplementary materials that could be found on the Internet.

5.2.3 Data collection

In this experiment, data were collected through four tools: test, questionnaire, learning log, and dialogue during group discussion.

The first tool is the test. Before the course, the pre-test, including tests 1–4 was conducted, to examine students' prior knowledge of the related contents they would learn over the next four weeks. After each week's lessons, students were required to take post-tests 1–4, respectively. All the problems in the tests were designed in collaboration with the teacher who conducted the STEM lessons, based on the science workbook of the experimental school, and the teaching objectives of this STEM course. The differences between pre-tests and post-tests were calculated to show the changes of students' understanding of the related knowledge and the ability to use their knowledge to solve scientific problems. As the aim of the activities in the first week was to introduce and familiarize students with the system, pre-post test 1 was not analyzed in this study.

The second tool is questionnaire. Two types of questionnaires, CPS Questionnaire and STEM Questionnaire were used in this experiment as pre-post questionnaires. In this study, the reliability of two questionnaires was assessed. The overall Cronbach's α value of the pre-CPS Questionnaire was 0.95, and the reliability of *Participation*, *Perspective taking*, *Social regulation*, *Task regulation*, and *Learning and knowledge building* was 0.83, 0.87, 0.81, 0.72, and 0.80, respectively. The overall Cronbach's α value of the post-CPS Questionnaire was 0.96, and the reliability of the five factors was 0.87, 0.87, 0.84, 0.71, and 0.86, respectively. Regarding the reliability of the STEM Questionnaires, the overall Cronbach's α value of the pre- STEM Questionnaire was 0.96, and the reliability of *Organizing*, *Elaborating*, *Repeating*, *Effort*, *Attention*, *Time management*, *Learning environment*, *Peer learning*, and *Using references* was 0.86, 0.86, 0.88, 0.78, 0.84, 0.84, 0.84, 0.84, and 0.79, respectively. The overall Cronbach's α value of post-STEM Questionnaire was 0.96, and the reliability of the nine factors was 0.86, 0.86, 0.90, 0.85, 0.71, 0.84, 0.84, 0.84, and 0.77, respectively.

The third tool is learning log. The data of learning logs on the *BookRoll* system were recorded to represent the frequency of students' behaviors when reading digital learning materials through this system. Nine types of learning logs (*Next*, *Previous*, *Page Jump*, *Add Marker*, *Delete Marker*, *Add Annotation*, *Delete Annotation*, *Add Bookmark*, *Delete Bookmark*) were collected.

Finally, the dialogues of discussion were recorded and coded, to clarify how students displayed their CPS skills when solving problems.

5.3 Results and Discussion

5.3.1 Changes in learning performance

RQ6-a: Did the learning performance change after the STEM lessons?

First, the paired sample t-test showed that the average test score was significantly improved after the lessons, from 24.22 to 64.75, at a significance level of $p < 0.001$ (**Table 12**). It is indicated that the instructional design, based on CPS processes and the integration of STEM fields, effectively promoted the acquisition of scientific knowledge.

Table 12 Paired sample t-test results of pre-post tests in Instructional practice 6

	Mean	SD	t value	*p* value
Pre-test	24.22	10.33	29.63^{***}	0.000
Post-test	64.75	15.40		

N=106; $^{***}p < 0.001$

5.3.2 Changes in CPS awareness

RQ6-b: Did each factor of CPS awareness change after the STEM lessons?

As for the changes of CPS awareness, *Participation* in social dimension and *Task Regulation* and *Learning and Knowledge Building* in cognitive dimension in CPS awareness were significantly improved after the lessons, and the specific results were presented in **Table 13**.

Table 13 Paired sample t-test results of pre-post CPS Questionnaires in Instructional practice 6

		Pre-questionnaire		**Post-questionnaire**		**t value**	***p* value**
		Mean	SD	Mean	SD		
Social dimension	***Participation***	11.84	2.605	12.58	2.611	2.545^{*}	0.012
	Perspective Taking	12.25	3.213	12.79	2.707	1.637	0.105
	Social Regulation	11.82	2.969	12.34	2.791	1.585	0.116
Cognitive dimension	***Task Regulation***	15.11	3.037	15.92	2.904	2.513^{*}	0.013
	Learning and Knowledge Building	15.68	3.360	16.57	3.272	2.431^{*}	0.017

N=106; $^{**}p < 0.01$, $^{*}p < 0.05$

5.3.3 Effects on the improvement of learning performance during the whole course

RQ6-c: What were the effects of students' learning behaviors, changes in the use of STEM learning strategies, and changes in CPS awareness on the improvement of learning performance?

In order to clarify what factors of students' CPS awareness would be affected by STEM learning strategies and learning behaviors and how these factors would influence the improvement of learning performance, path analysis was conducted to explore students' learning behavior and strategic effects on the improvement of learning performance for CPS-based STEM learning.

First, the indicators of model fitting were evaluated. The indicators $\chi^2(46) = 57.807$, CFI = 0.974, TLI=0.967, RMSEA = 0.049, and AIC=10830.493 indicated that the model fit the data well. All paths met the significance level of $p < 0.05$.

The second step was evaluating the structural model. Each factor of the CPS awareness and STEM learning strategy is the average difference between pre-post questionnaires. As presented in Figure 12, the results indicated that the factors of learning behaviors and changes in CPS awareness directly affected on learning performance improvement. Changes in STEM strategy use had indirect effects on learning performance improvement, which was mediated by changes in CPS awareness.

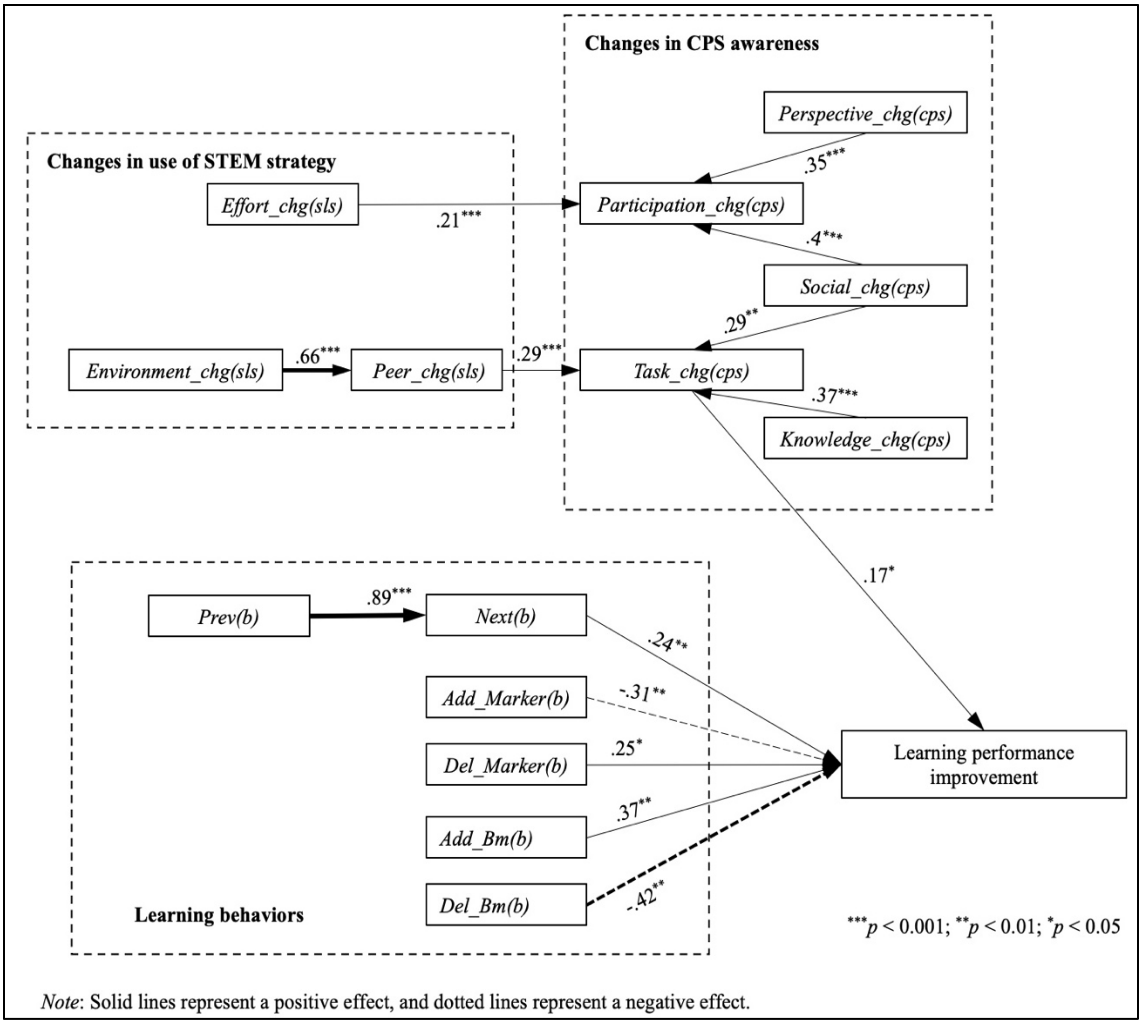


Figure 12. Path analysis results of the behavioral and strategic effects during the whole course

Direct effects

First, the direct effects of the independent variables on learning performance improvement were examined, which was the dependent variable.

Regarding CPS awareness, the results showed that an increase of *Task_chg* (*Task Regulation*) awareness promoted learning performance improvement. However, other factors in CPS awareness did not show the direct effects on learning performance improvement. Among five factors, the increase of *Social_chg* (*Social Regulation*) and *Knowledge_chg* (*Learning and Knowledge Building*) showed indirect positive effects on learning performance improvement, mediated by an increase of *Task_chg*.

As for the learning behaviors, *Next*, *Del_Marker* (*Delete Marker*), and *Add_Bm* (Add *Bookmark*) showed direct positive effects on learning performance improvement. It was indicated that when students conducted these behaviors more frequently, their test scores were more likely to improve. Moreover, *Prev* (Previous) was shown to positively affect learning performance improvement when mediated by *Next*. On the other hand, the results also revealed that *Add Marker* (*Add Marker*)and *Del_Bm* (*Delete Bookmark*) had negative effects on learning performance improvement, from which it can be inferred that students' frequent behaviors of adding markers or deleting bookmarks would be harmful to their test scores.

However, there was no direct effect found of changes in STEM strategy use on learning performance improvement.

Indirect effects

To examine the mediation effect of changes in CPS awareness between independent and dependent variables, two indirect effects were examined: changes in STEM strategy use and learning behaviors to learning performance improvement. In this study, the indirect effect was only found from changes in STEM strategy use to learning performance improvement.

Specifically, changes in the use of *Peer_chg* (*Peer learning*) in the STEM learning strategy showed a positive effect on learning performance improvement, mediated by changes in *Task_chg* awareness. Moreover, an increase of using the *Environment_chg* (*Learning environment*) strategy promoted the *Peer_chg* strategy. In addition, although there was no effect on learning performance improvement, the increase of using the *Effort_chg* strategy was showed to improve the *Participation_chg* awareness.

5.3.4 Effects on the improvement of learning performance in three learning phases
RQ6-d: What were the effects of students' learning behaviors on the improvement of learning performance in different learning phases?

5.3.4.1 Path of causal relationships

Path analysis was conducted to examine the causal relationships between students' learning behaviors and their learning performance and see how learning behaviors and prior knowledge affected learning performance in each learning phase. The results of the path analysis are presented in Figure 13.

In Phase 1 (*Learning and practice*), the learning behaviors of *Previous_1* revealed a direct positive effect, while *Delete Red Marker_1* indicated a direct negative effect on the score of Test_1. In Phase 2 (*Reinforcement*), the score of Test_1 and the learning behavior of *Delete Memo_2* revealed direct positive effects on the score of Test_2. Although *Add Memo_2* had no direct effect, it indicated indirect positive effects on the score of Test_2, mediated by *Delete Memo_2*. In Phase 3 (*Application*), the score of Test_1 and the learning behavior of *Page Jump_3* revealed direct positive effects on the score of Test_3.

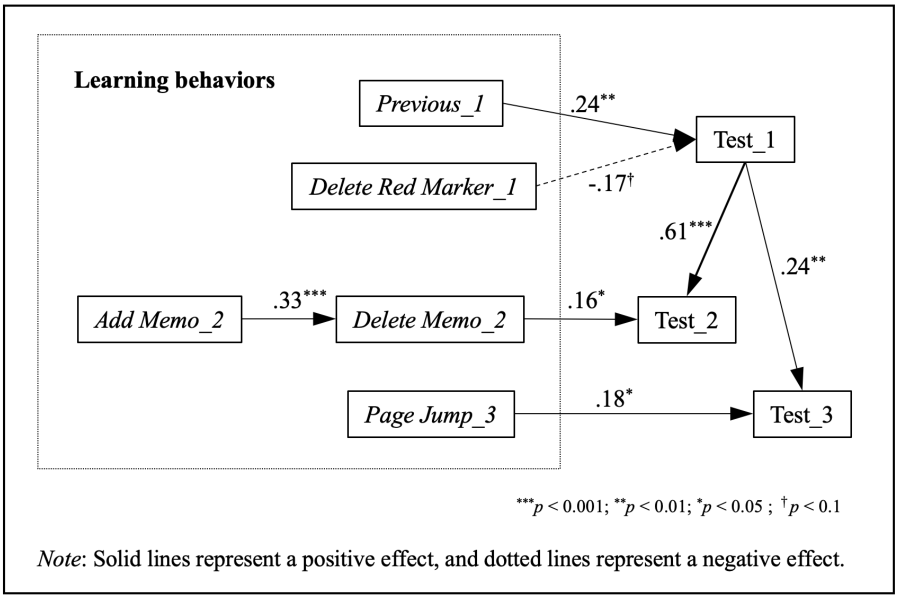


Figure 13. Path analysis results of the behavioral effects in three phases

5.3.4.2 Relationships between learning behaviors in three phases and learning strategies

In order to provide students with appropriate instructions regarding what STEM strategies are effective and how to use them, it is necessary to connect students' learning behaviors with their perceptions of the use of STEM learning strategies and the teachers' instructions. Therefore, we used Pearson's correlation coefficient to examine the relationships between the use of STEM learning strategies and effective learning behaviors according to the results of path analysis and discussed these learning behaviors based on the teachers' instructions. According to the results of Pearson's correlation coefficient, there were weak correlations between the learning behavior of *Add Memo_2* with Attention of STEM learning strategy ($r = 0.217$, $p < 0.05$), *Page Jump_3* behavior with *Using Reference* strategy ($r = 0.212$, $p < 0.1$).

Moreover, in CPS learning, it is necessary to integrate some cognitive strategies (such as organization and elaboration) and metacognitive strategies (such as reflection) into CPS processes. Based on the results and the discussion, I proposed a design of a CPS-based STEM course by integrating the effective learning behaviors and STEM learning strategies in different phases. The result of the connections between learning behaviors and learning strategies in three phases is shown in Figure 14.

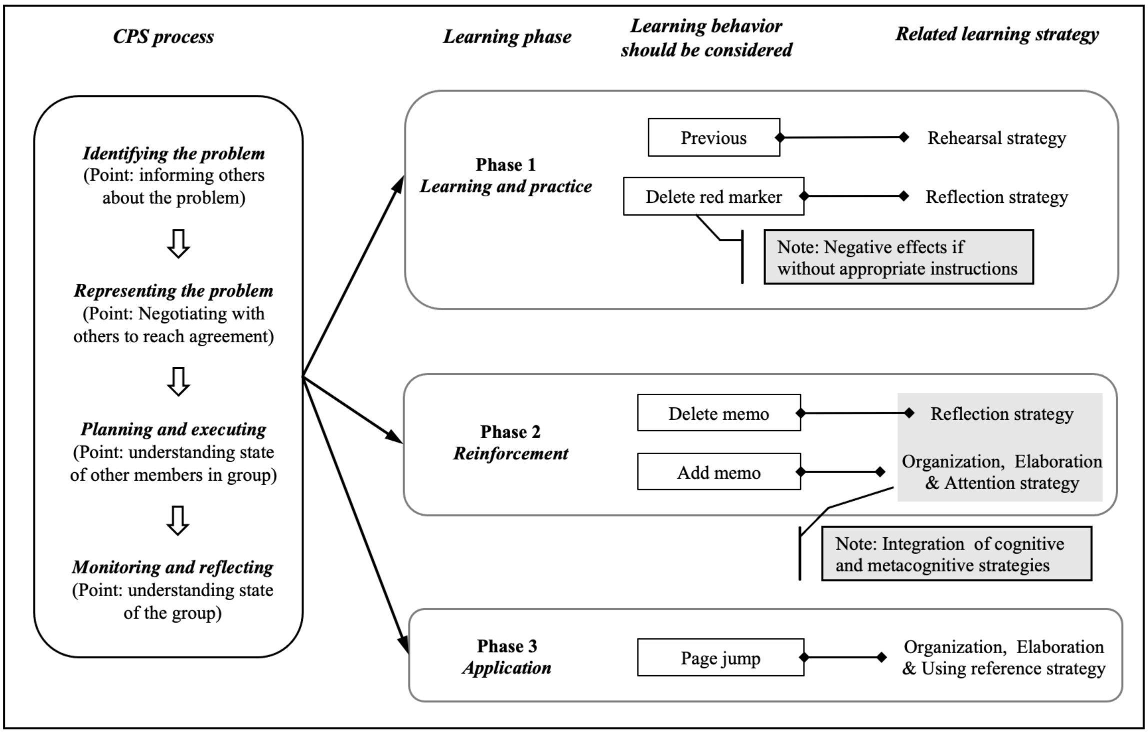


Figure 14. Results of the connections between learning behaviors and STEM learning strategies in three phases

5.3.5 Effects on the improvement of learning performance and CPS awareness during in-class and out-of-class learning

RQ6-e: What factors of learning behavior affected the improvement of learning performance and CPS awareness during in-class and out-of-class learning?

5.3.5.1 Descriptive data

To determine the different effects of learning behaviors on outcomes during different learning activities, the numbers of learning behaviors during in-class and out-of-class learning were calculated. Multiple regression analysis was conducted to investigate the effect of these behaviors on learning performance and CPS awareness. The sum of the number of learning behaviors during in-class and out-of-class learning was set as the independent variable. The descriptive data of two dependent variables, namely the differences in learning performance and CPS awareness, and learning behaviors during in-class and out-of-class learning as the independent variables, are presented in **Table 14**.

Table 14 Descriptive data of dependent and independent variables

Variable		Mean	SD	Minimum	Maximum
Dependent variable	Differences in learning performance	40.53	14.01	8	75
	Differences in *Participation*	0.74	2.96	−11	10
	Differences in *Perspective Taking*	0.54	3.37	−10	12
	Differences in *Social Regulation*	0.52	3.35	−9	12
	Differences in *Task Regulation*	0.81	3.31	−9	11
	Differences in *Learning and Knowledge Building*	0.89	3.74	−10	15
Independent variable	*Next_in*	129.10	61.07	15	353
	Previous_in	62.08	53.92	0	316
	Page Jump_in	8.76	10.36	0	70
	Add Marker_in	32.72	34.99	0	217
	Del Marker_in	11.90	23.55	0	180
	Add Memo_in	6.94	6.22	0	24
	Del Memo_in	0.38	0.87	0	5
	Add Bookmark_in	3.18	1.506.92	0	55
	Del Bookmark_in	1.50	3.82	0	28
	Next_out	28.11	48.52	0	336
	Previous_out	14.34	29.09	0	186
	Page Jump_out	1.54	3.77	0	28
	Add Marker_out	6.37	13.74	0	80
	Del Marker_out	2.13	5.67	0	35
	Add Memo_out	0.86	2.33	0	12
	Del Memo_out	0.11	0.44	0	3
	Add Bookmark_out	0.51	1.66	0	13
	Del Bookmark_out	0/31	1.20	0	9

5.3.5.2 Effects on the improvement of learning performance

When the difference in learning performance was set as the dependent variable, no independent variable of learning behaviors met the criteria for entry into the model. It is indicated that the learning behaviors during in-class and out-of-class learning separately did not improve the learning performance directly.

5.3.5.3 Effects on the improvement of CPS awareness

As the improvement of CPS awareness, the differences in each CPS factor were set as the dependent variables. As a result, when the change in the *Social Regulation* in CPS was the dependent variable, the independent variables *Add Marker_out* ($\beta = 0.194$, $p = 0.046$) remained significant for the full model. This variable accounted for 2.8% of the variance of the dependent variable change in the *Social Regulation*: $F(1, 104) = 4.077$, $p = 0.046$. The results are shown in **Table 15**. The regression coefficients indicated that an increase in the learning behaviors of adding markers during students' individual learning promoted students' *Social Regulation* awareness. *Social Regulation* means the strategies students use to regulate their collaborative activities. In their individual learning, including preview and review work, students were required to use a marker tool to highlight the important contents or the contents they do not understand well. From the results, it is indicated that understanding the learning materials and acquiring background knowledge was helpful for students to regulate their collaborative activities.

Table 15 Results of regression analysis predicting *Social Regulation* improvement with learning behaviors during in-class and out-of-class learning (N=106)

Variable	B	SE B	*β*	*T*
Add Marker_out	0.047	0.023	0.194	2.019^{*}

$R^2 = .038$, Adjusted $R^2 = .028$, $^{*}p < .05$

When change in the *Learning and Knowledge Building* in CPS was the dependent variable, the independent variables *Add Marker_out* ($\beta = 0.420$, $p = 0.002$) and *Del Marker_out* ($\beta = -0.301$, $p = 0.027$) remained significant for the full model. These two variables accounted for 7.4% of the variance of the dependent variable change in the *Learning and Knowledge Building*: $F(1, 104) = 9.338$, $p = 0.003$. The results are shown in **Table 16**. The regression coefficients indicated that an increase in the learning behaviors of adding markers during students' individual learning promoted students' *Learning and Knowledge Building* awareness. However, the *Learning and Knowledge Building* awareness of students who were deleting markers more frequently during the individual learning tended to decrease. *Learning and Knowledge Building* focuses on students' ability to understand and identify the relationships, cause and effect of the knowledge. Same as the previous results, understanding learning contents in advance using marker tools effectively improved students' knowledge building and understanding during the collaborative activities. However, the learning behavior of deleting marker showed a negative effect on the improvement of *Learning and Knowledge Building* awareness. Students were required to delete the markers they added previously when they changed the ideas after the group discussion or teacher's explanation. Thus this behavior was connected to the reflection strategy. This result indicates that students' reflection is insufficient and cannot support the improvement of knowledge building and understanding.

Table 16 Results of regression analysis predicting *Learning and Knowledge Building* improvement with learning behaviors during in-class and out-of-class learning (N=106)

Variable	B	SE B	*β*	*T*
Add Marker_out	0.416	0.133	0.420	3.135**
Del Marker_out	-0.723	0.322	-0.301	-2.247*

R^2 = .082, Adjusted R^2 = .074, $^{**}p < .01$, $^{*}p < .05$

5.3.6 Differences in effects on the improvement of learning performance and CPS awareness between high and low learning performers

RQ6-f: Between high and low learning performers, what was the difference in strategic and behavioral factors that influence learning performance and CPS awareness?

In this instructional practice, since it is assumed that the individual cognitive differences of learners would affect their acquisition of new knowledge and learning awareness, students were divided into two groups, high-performance and low-performance groups, according to their pre-test scores. The students who gained a pre-test score in the top 25 percentile (first quartile) were categorized into the high-performance group (N = 21, Mean = 39.14), and those who gained a pre-test score in the bottom 25 percentile (third quartile) were classified as the low-performance group (N = 28, Mean = 11.57).

First, the significant differences in factors of the changes in learning performers and each factor in CPS awareness were examined to see whether individual differences regarding the prior knowledge affected their acquisition of knowledge and CPS awareness. The results showed no significant different in these factors between high and low learning performance groups.

Next, Spearman's Rank Correlation Coefficient was used to investigate the relationships among the changes in learning performance and CPS awareness with STEM learning strategies and learning behaviors and compared the results of high-performance and low-performance groups.

As for the relationships between learning performance improvement with strategic and behavioral factors, only one factor of STEM learning strategy, *Attention*, showed a moderate positive relationship with learning performance improvement ($\rho = 0.514$, $p = 0.017$) in the high-performance group. However, there was no significant relationship found in the low-performance group.

As for the relationships between CPS awareness improvement with strategic and behavioral factors in the high-performance group, first, regarding the social dimension in CPS awareness, moderate positive relationships were found between *Repeating* strategy with *Participation* awareness ($\rho = 0.473$, $p = 0.030$), *Time Management* strategy with *Social Regulation* awareness ($\rho = 0.494$, $p = 0.023$), and strong positive relationships between *Time Management* strategy with *Perspective Taking* awareness ($\rho = 0.667$, $p = 0.001$). Regarding the cognitive dimension in CPS awareness, moderate positive relationships were found between *Reference* strategy with *Learning and Knowledge Building* awareness ($\rho = 0.441$, $p = 0.045$), strong relationships between *Planning* strategy with *Task Regulation* awareness ($\rho = 0.581$, $p = 0.006$) and *Learning and Knowledge Building* awareness ($\rho = 0.678$, $p = 0.001$).

In low-performance group, first, regarding the social dimension in CPS awareness, moderate positive relationships were found between *Effort* ($\rho = 0.466$, $p = 0.012$) and *Using Reference* ($\rho = 0.398$, $p = 0.036$) strategy with *Participation* awareness, strong positive relationships between *Time Management* ($\rho = 0.533$, $p = 0.003$) and *Planning* strategy ($\rho = 0.510$, $p = 0.006$) with *Participation* awareness; moderate positive relationships between *Elaborating* ($\rho = 0.481$, $p = 0.010$), *Repeating* ($\rho = 0.467$, $p = 0.012$), *Using Reference* ($\rho = 0.491$, $p = 0.008$) strategy with *Perspective Taking* awareness; moderate positive relationships between *Time Management* ($\rho = 0.443$, $p = 0.018$), *Planning* ($\rho = 0.494$, $p = 0.008$), *Using Reference* ($\rho = 0.432$, $p = 0.022$) strategy with *Social Regulation* awareness. Regarding cognitive domain, moderate positive relationship was found between *Using Reference* ($\rho = 0.464$, $p = 0.013$), and moderate positive relationships between *Organizing* ($\rho = 0.411$, $p = 0.030$), *Time Management* ($\rho = 0.496$, $p = 0.007$), *Using Reference* ($\rho = 0.467$, $p = 0.012$) strategy with *Learning and Knowledge Building* awareness, and strong positive relationships between *Elaborating* ($\rho = 0.555$, $p = 0.002$) and *Planning* ($\rho = 0.532$, $p = 0.004$) with *Learning and Knowledge Building* awareness. From the results above, it is indicated that both high and low performers showed positive relationships between their perception of using STEM strategies with the improvement of CPS awareness, and the low performers showed more connections between these two factors.

In order to find out the relationships regarding students' actual behaviors in addition to their perceptions, the relationships between learning behaviors and CPS awareness improvement were examined. As the results, first, in the high-performance group, strong positive relationships were found between *Del Memo* behavior with *Participation* ($\rho = 0.540$, $p = 0.011$) and *Perspective Taking* awareness ($\rho = 0.573$, $p = 0.007$), while a moderate negative relationship was found between *Add Bookmark* with *Task Regulation* ($\rho = -0.485$, $p = 0.026$). However, there was no significant relationship found in the low-performance group. It is indicated that the use of cognitive tools such as memos could help the development of social awareness with a specific level of prior knowledge.

5.3.7 Dialogue analysis

RQ6-g: How did students display CPS skills during the discussion?

In RQ6-c, the path analysis revealed causal relationships among factors of CPS awareness and showed direct and indirect effects on the improvement of learning performance. In the path analysis, *Task Regulation* awareness showed a direct positive effect on the improvement of learning performance, *Social Regulation* and *Learning and Knowledge Building* awareness showed indirect effects on the improvement of learning performance, mediated by *Task Regulation* awareness. Moreover, *Social Regulation* and *Perspective Taking* showed a direct positive effect on *Participation* awareness.

In order to investigate whether students used these skills to solve the problems during the lessons and whether these skills students used had mutual effects as a result of the path analysis, the dialogue analysis was conducted. The dialogue data were analyzed during students' group discussion and categorized dialogue thread concerning five sub-skills and 18 elements of CPS (the descriptions of each element are presented in Table 1, p 8~10 in this dissertation). However, not all factors in CPS were found during the discussion. Since the first week was designed for practice and the data were not analyzed in this week, dialogue data were analyzed the latter three topics, (a) *Use of acid and alkali solutions*, (b) *Acid Rain*, (c) *Limnic Eruption*. Three main problems for students to solve are as follows:

(a) *Use of acid and alkali solutions* (Week 2)

What examples of using acid and alkali solutions do you know in daily life?

(b) *Acid Rain* (Week 3)

Several years ago, there was news circulating on the Internet. 'In the following month, please do not forget to bring your umbrellas when you go out. Do not get exposed to the rain! The acid rain which occurred 750 years ago occurred now, and people will have a high chance of suffering from various skin diseases if exposed to this rain. The volcano in Iceland in Europe erupted, a large amount of sulfide was ejected into the air and formed thick volcanic ash at an altitude of 7000 to 10000 meters in the atmosphere. Do not be exposed to the rain this month!'

Do you think whether this news is true or false?

(c) *Limnic Eruption* (Week 4)

Lake Nyos is a crater lake in Cameroon. In 1986, massive amounts of dissolved CO_2 *suddenly erupted from the bottom of the lake and caused a limnic eruption. The eruption caused asphyxiation and the death of around 1700 people living nearby. There is still concern about recurring gas hazards.*

What is the reason for this Limnic Eruption?

5.3.7.1 Relationships between the use of each CPS sub-skills compared with path analysis results

In order to examine whether students' display of CPS skills is the same as their CPS awareness, I first analyzed the related factors which had causal relationship according to the path analysis, which were *Perspective Taking* and *Participation*, *Social Regulation* and *Participation*, *Social Regulation* and *Task Regulation*, *Learning and Knowledge Building* and *Task Regulation*.

(1) *Perspective Taking* and *Participation*

In path analysis, the results showed that students' *Perspective Taking* awareness positively affected their *Participation* awareness. Therefore, I coded students' discussions in which they used *Perspective Taking* and *Participation* skills according to Hesse et al.' (2015) CPS framework and analyzed the relationship between the use of these two skills.

Three cases were identified which showed the relationship between the use of these two skills. Three cases are all in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 1 (Group 1, Class 1) *Participation* → *Perspective Taking*		
Interaction (*Participation*) Adaptive responsiveness (*Perspective Taking*)	32. S1: I will search for the information for you. 33. S3: OK, then we should share our screen and discuss. 34. S1: I have searched for you. See, here are the contents. 35. S3: Good job.	This case shows how students display Interaction and Adaptive responsiveness skills in one task. Interaction in *Participation* refers to the activities of responding to others' contributions and interacting with others. Adaptive responsiveness in *Perspective Taking refers to a*ccepting or adapting others' contributions. Both of these elements contain responding to others' contributions, and the difference is that adaptive responsiveness does not contain interactive behaviors with others. In Lines 33~34, S3 accepted the suggestion from S1 and further proposed the following actions for them regarding S1's suggestion. Therefore, these

		dialogues were identified as actions regarding Interaction. In Line 35, S3 recognized S2's contribution and showed praise for S2. Since there are no interactive activities after this dialogue, it is identified as Adaptive responsiveness here. In this case, students conducted interaction (*Participation*) and then accepting and responding to others' contributions (*Perspective Taking*) through the interaction.
Case 2 (Group 1, Class 1) *Perspective Taking* → *Participation*		
Adaptive responsiveness (*Perspective Taking*) Interaction (*Participation*)	47. S3: I think the air should be ventilated. <u>48. S1: Yes, I think so too.</u> 49. S3: Because it is written on the learning material, in the beginning. 50. S1: Ventilate the air, and use the air purifier. 51. S3: To reduce concentration. <u>52. S1: (Taking a memo) use the air purifier, to reduce concentration. What else?</u> <u>53. S3: Ventilate the air.</u> 54. S1: Yeah, I have found this information on the Internet.	In Line 48, S1 showed agreement to S3's answer, and in Line 50, S1 repeated this answer and supplemented this answer. It is indicated that S1 *a*ccepted and adapted S3's contributions. In Line 52, S1 took a memo of S3's contribution for the latter group discussion, which showed S1's acceptance of S3's contribution. Then, in order to take a more detailed memo, S1 asked for more details, and S3 helped to recall the former answer, which showed the interaction between them. In this case, students reached an agreement on the contributions (*Perspective Taking*), and then they collaboratively took the memo about the contributions for the later presentation (*Participation*).
Case 3 (Group 7, Class 3) *Perspective Taking* ↔ *Participation*		
	326. S1: Turn to the next page. I	In this case, an example of using

Adaptive responsiveness (*Perspective Taking*) & Interaction (*Participation*)	think it's because… 327. S2: Carbon dioxide, carbon dioxide, because carbon dioxide is deposited here, and then the water mergers with carbon dioxide. If there is an earthquake or something, the rock will loosen up. 328. S1: (Reading leanring material) Magma is the rock that is molten or partially molten underground. 329. S2: (Keep reading) It dissolves gases such as carbon dioxide, water vapor and sulfur dioxide. (Explaining) Because, because, because it is a molten rock under magma, carbon dioxide, water vapor and sulfur dioxide are dissolved inside. Because of the sedimentation, and then, in these magma sediments, a large amount of carbon dioxide is released. 330. S1: Then the carbon dioxide is dissolved in the water. Then, if there is an earthquake or a landslide shakes, the rock will loosen up, the gas will rush upwards, and then it will explode.	Interaction an Adaptive responsiveness skill at the same time. In Lines 326~329, S1 and S3 searched for the information for the learning materials at the same pace and complemented information mutually. Moreover, in Line 329, S1 provided the explanation about the contents of learning materials, and then in Line 330, S2 continued S1's explanation and provided a complete explanation about why CO_2 erupted. This case contained elements of both Adaptive responsiveness (*Perspective Taking*) and Interaction (*Participation*) because S1 and S2 constructed the dialogue while responding to each other's contributions.

From the above three cases, it is indicated that the use of *Perspective Taking* and *Participation* skills showed mutual effects on each other, rather than one-way causality. In Case 1, students conducted interaction by using *Participation* skill and then accepting and responding to others' contributions through the interaction by using *Perspective Taking* skill. In Case 2, students reached an agreement of the contributions by using *Perspective Taking* skill, and then collaboratively took the memo about the contributions for the later presentation by using *Perspective Taking* skill. In Case 3, students used Interaction (in *Participation*) and *Adaptive responsiveness* (in *Perspective Taking*) skills simultaneously, by constructing the dialogue while responding to each other's contributions.

However, one element in the *Participation,* Action, is not identified during the dialogue analysis. Because the element of Action refers to all activities in the collaborative environment, all the discussion could be seen as the actions in the collaborative environment. Therefore, it is difficult to exclude the Action element and identify the relationship between the Action element with other elements.

(2) *Social Regulation* and *Participation*

The relationship between *Social Regulation* and *Participation* is not identified. The first reason is the difficulty of identifying the Action element during the discussion. When examining the relationship between other elements, no elements in *Social Regulation* and *Participation* are found in the same group in each topic.

(3) *Social Regulation* and *Task Regulation*

In path analysis, the results showed that students' *Social Regulation* awareness positively affected their *Task Regulation* awareness. Here, two cases were identified which showed the relationship between the use of these two skills. Case 4 is in the (a) *Use of acid and alkali solutions* topic, and Case 5 is in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 4 (Group 3, Class 3) *Social Regulation →Task Regulation*		
	25. S2: The bees leave the acid in there (skin). 26. S1: How do you know it's acid? 27: S2: Because it is written here, formic acid. So it must be an acidic solution. 28. S1: So we should apply some alkaline substances. Which alkaline substance do	Responsibility initiative refers to assuming responsibility for ensuring parts of the task are completed by the group. Collects elements of information refers to actions of exploring and understanding elements of the task, what information is valuable, and how to use this information. In Lines 25~32, students discussed

Responsibility initiative (*Social Regulation*) Collects elements of information (*Task Regulation*)	you know? 29. S2: Like this (showing the information). Like, laundry powder? 30. S1: Isn't this acid? 31. S2: It's alkaline. 32. 1: Yes, it's alkaline. When we use acidic solution and alkaline solution… 33. S2: Wait, wait. Let me take a note. OK, next, next question. 34. S1: Next, we should discuss this question. What examples of using acid and alkali solutions do you know in daily life? 35. S2: If you are bitten by a mosquito, you can apply something to the skin. But I don't know now. I don't know what the mosquito left is acidic or alkaline. It isn't written in the textbook, so we should search for it on the Internet.	which solution is acid or alkaline. In Line 33, S1 took the responsibility to take the notes for the group as the preparation for the later presentation, which showed the use of Responsibility initiative skill. In Line 35, when the group wanted to know the acidity and alkalinity of the solution, S2 first confirmed the information in the textbook and then suggested searching for relevant information on the Internet. This behavior is related to collects elements of information skills. Therefore, in this case, students first conducted a discussion to reach an agreement about the given problem, and one student took the responsibility to complete the task for the whole group (*Social Regulation*). Based on the agreement, they summarized the points and the missed information for the problem (*Task Regulation*).
Case 5 (Group 4, Class 1) *Social Regulation* ↔ *Task Regulation*		
Negotiation (*Social Regulation*)	106. S2: Carbon dioxide and the lake, we can imagine it as Cola. 107. S1: Is that acid? Is cola acid? 108. S2: Cola is acid. 109. S1: I haven't checked the textbook. 110: S3: Cola is alkaline. 111. S2: I think Cola is acid.	Negotiation refers to the efforts and actions to achieve a resolution or reach a compromise. In Lines 110~117, students in this group conducted a negotiation about whether Cola is acidic or alkaline. When S2 and S3 had different opinions about the answer (Lines 110~111), S3 proposed to search for the information on the Internet (Line 112). However, S2 ignored S3's proposal

Collects elements of information (*Task Regulation*)	112. S3: Let's search for that on Baidu (one kind of search engine). 113. S2: Is Cola alkaline? 114. S1: Cola is acid. Soda water is alkaline. 115. S3: Let's search for that. Cola is acid. 116. S1: How do you know? 117. S3: From Baidu. Cola is a carbonated drink.	(Lines 113~114). So S3 searched for the information individually, and then S3 reported the results to others to reach an agreement within the group (Line 115). In this case, students conducted a negotiation about one specific knowledge (*Social Regulation*), and they used Collects elements of information skill to reach agreement (*Task Regulation*) during the negotiation.

The above two cases indicate that the use of *Social Regulation* and *Task Regulation* skills showed mutual effects on each other, rather than one-way causality. In Case 4, students first conducted a discussion and reached an agreement. Then one student took responsibility for the whole group by using *Social Regulation* skill. Finally, they collected information for the problem based on the agreement by using Task *Regulation* skill. In Case 5, students conducted a negotiation about one specific knowledge using *Social Regulation* skill, and they used Collects elements of information in *Task Regulation* skill to reach an agreement during the negotiation.

(4) *Learning and Knowledge Building* and *Task Regulation*

In path analysis, the results showed that students' *Learning and Knowledge Building* awareness positively affected their *Task Regulation* awareness. Four cases were identified which showed the relationship between the use of these two skills. The first case is in the (b) *Acid rain* topic, and the other three cases are in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 6 (Group 2, Class 3) *Task Regulation → Learning and Knowledge Building*		
Problem analysis/Collects elements of information (*Task Regulation*)	17. S3: What is acid rain? Is it related to its pH value? It is written here. pH < 5.6, right? 18. S1: Yes, I think it's difficult, in winter, the acid rain. 19. S3: I think the news is fake. At that time, the Icelandic	This case shows the relationships between the use Problem analysis skill in *Task Regulation* and Rules: "If…then" skill in *Learning and Knowledge Building*. It is the only case that shows the use of Rules: "If…then" skill.

Collects elements of information (*Task Regulation*) Rules elements of information (*Task Regulation*)	volcano erupted and formed the, what was that called?_ That is, when it reaches 7,000 to 10,000 meters in the atmosphere, I think the pH value can't reach 5.6. 20. S2: Yes. So it can't form the acid rain. 21: S3: On the other hand, even the acid rain is formed, when you go out, your skin might be infected by the virus. No, I mean, the skin disease. 22. S2: So we shouldn't go out. 23: S3: If there such acid rain happens, I suggest not to go out. But I don't know, whether the acid rain will be formed. I think we should examine the pH value, to see whether it is 5.6. If the result shows it isn't acid rain, or won't cause such disease, it's ok. But it is better to take protection when going out. It is said that the probability of skin diseases may be very high. It's the probability, we don't know, so we should examine it.	In Line 17, S3 analyzed the point of the problem and confirmed the definition of acid rain, which was one of the most important points of the problem, according to the provided information. Then S3 provided the subsequent explanations based on the definition of acid rain. In Line 19, S3 inferred that the pH value could not reach 5.6 based on the provided information from the learning materials. In Line 23, S3 understood the points of the problem, and the cause and effect of the pH value and the harmfulness of acid rain. Therefore, S3 set a plan to examine the pH value first, then to judge whether the rain was harmful and what kind of diseases it would cause. In this case, students used *Task Regulation* skill to analyze the points and the knowledge in the problem, and used *Learning and Knowledge Building* skill to construct knowledge based on the understanding of the problem.
Case 7 (Group 3, Class 3) *Task Regulation → Learning and Knowledge Building*		
	180. S1: Let's Baidu. 181. S2: No, don't Baidu, you can't find the answer on Baidu. 182: S1: Really?	Relationships refers to the ability to identify relationships between and among elements of knowledge. In Lines 183~185, and Line 189~190, S1 and S2 discussed how to read

Resource management (*Task Regulation*) Collects elements of information (*Task Regulation*) Relationships (*Learning and Knowledge Building*)	183. S2: I open the preview (learning material for preview). 184. S1: OK, I open the other material. 185. S2: Look. 186. S1: OK, we can see these two learning materials at the same time. (S1 is Searching for information on the Internet.) 187. S2: You can't find the answer on Baidu. 188. S1: Really? Disaster. (Typing) The reason for the Limnic Eruption… 189. S2: Open the preview (material) now! 190. S1: OK. … 197. S2: Why did carbon dioxide erupt? 198. S1: It is written here, the same principle of the carbonated drink. But it not always erupts. Sometimes, like last time, I shook, but it didn't spurt out. I don't know the reason. We should search for that.	provided learning materials by the management of labor. In Line 188, S1 tried to seek further information or more direct information through the Internet. In Line 198, S1 found the relevant information on the learning materials and related this knowledge with his previous experience. In order to understand the reason for Limnic Eruption, which S1 and S2 could not conclude from the provided learning materials, S1 proposed to search for further information on the Internet. In this case, students used some skills of *Task Regulation* to identify the valuable information for the problem and identified relationships between the point of the problem and their prior knowledge.
Case 8 (Group 3, Class 4) *Task Regulation* ↔ *Learning and Knowledge Building*		
Relationships (*Learning and	44. S1: Why did carbon dioxide erupt? 45. S2: Just like the Cola. The carbon dioxide in the magma is released into the air, causing the	In this case, students also used Collects elements of information skill in *Task Regulation* and Relationships skill in *Learning and Knowledge Building*, as in Case 6.

Knowledge Building)	water in the lake to be pressed out, and then carbon dioxide erupts into the air, making people unable to breathe. 46. S1: If there is no change in the lake, it won't erupt, right?	In Lines 45, 47, and 52, S2 explained the Limnic Eruption mechanism by using the example of the Cola, which students are familiar with. In Lines 48~51, students connected the information from the learning material with S2's explanation, so in Line 52, S2 supplemented his explanation based on the information they discussed. In this case, the relationships between the use of *Regulation* skill and *Learning and Knowledge Building* skill are the same as in Case 6. Students used *Task Regulation* skill to seek information and *Learning and Knowledge Building* skill to make connections between the current information with their familiar knowledge repeatedly.
Relationships (*Learning and Knowledge Building*)	47. S2: Oh, I got it, I got it. That is, there are volcanic lakes below it, and then there is magma below it. And then the magma released carbon dioxide gas, and then because there was a rock above it, it is said that the gas cannot be released. It bursts out. Then this lake which is dissolved a large amount of carbon dioxide erupted.	
Collects elements of information (*Task Regulation*)	48. S1: So it's because of the earthquake? The carbon dioxide in the magma. 49. S3: What earthquake? 50. S2: It is written here (the learning material). 51. S1: It is said that may be an earthquake occurred.	
Relationships (*Learning and Knowledge Building*)	52. S2: So, then, the carbon dioxide in the magma would be full of the lake, because the top is closed. That is, the hole, the rock, I mean the eruption port, are closed. Because the hole for the eruption was closed, just like you put the cap on a Cola bottle, the earthquake is just like shaking the bottle, and then it will erupt.	

	53. S1: Yeah, that's what I mean.	
Case 9 (Group 8, Class 3) *Task Regulation* ↔ *Learning and Knowledge Building* → *Perspective Taking*		
Relationships (*Learning and Knowledge Building*) Collects elements of information (*Task Regulation*) Relationships (*Learning and Knowledge Building*) Adaptive responsiveness (*Perspective Taking*)	<u>384. S1: Just like shaking a sealed bottle of Cola vigorously. There is a large amount of carbon dioxide and sulfur dioxide dissolved in the water.</u> 385. S2: And it spurts out fiercely. So in the Limnic Eruption, because of the earthquake, which is written in the textbook, the rocks in the lake dispersed. <u>386. S1: Yes, the earthquake is just like shaking the bottle of Cola vigorously. So carbon dioxide will spurt out.</u> 387. S2: Yes, the rocks in the lake will be dispersed, and the accumulated carbon dioxide will erupt.	In this case, students used Relationships skill in *Learning and Knowledge Building* to used familiar examples to help them understand the knowledge, then used Collects elements of information skill in *Task Regulation* to analyze the elements of the information, and finally used Adaptive responsiveness to show their acceptance and response to others' contributions. In Line 384, S1 related the phenomenon of Limnic Eruption with the Cola in their daily life, which had a similar phenomenon and principle with Limnic Eruption. In Line 385, S2 accepted the connection between Limnic Eruption and the Cola and find out the important information from the learning materials, which was the reason that caused the change in the lake. In Line 386, S1 connected S2's contribution with the phenomenon of Cola to help understand why an earthquake would cause the change in the lake. Finally, in Line 387, S2 showed his acceptance for S1's contributions by repeating S1's explanation, and summarized the final answer based on the group's contribution. In this case, in order to understand

		unfamiliar knowledge, students used *Task Regulation* skill to seek information, and *Learning and Knowledge Building* skill to make connections between the current information with their familiar knowledge repeatedly. In this case, the Learning and Knowledge Building skill was used as a tool to understand the unfamiliar knowledge, and it was effective for students to accept and adapt others' contributions by using these skills.

The above four cases indicated that the use of *Learning and Knowledge Building* and *Task Regulation* also showed mutual effects on each other, rather than one-way causality. Moreover, one difference from the result of path analysis, in Case 6 and 7, students used some skills of *Task Regulation* to analyze the problem and identify the valuable information for the problem and then used *Learning and Knowledge Building* skills to construct knowledge. Therefore, the *Task Regulation* skill is considered to affect the *Learning and Knowledge Building* skill. Case 8 and 9 showed the same relationship pattern between these two sub-skills. In these two cases, in order to understand unfamiliar knowledge, students used *Task Regulation* skill to seek information, and *Learning and Knowledge Building* skill to make connections between the current information with their familiar knowledge repeatedly.

According to the above results, it is indicated that although the results of path analysis showed the causal relationship between each factor of CPS awareness, actually when students used CPS skills during group work, the use of CPS skills showed mutual effects on each other, rather than simple one-way relationship. The results of the path analysis and dialogue analysis regarding CPS were compared in Figure 15.

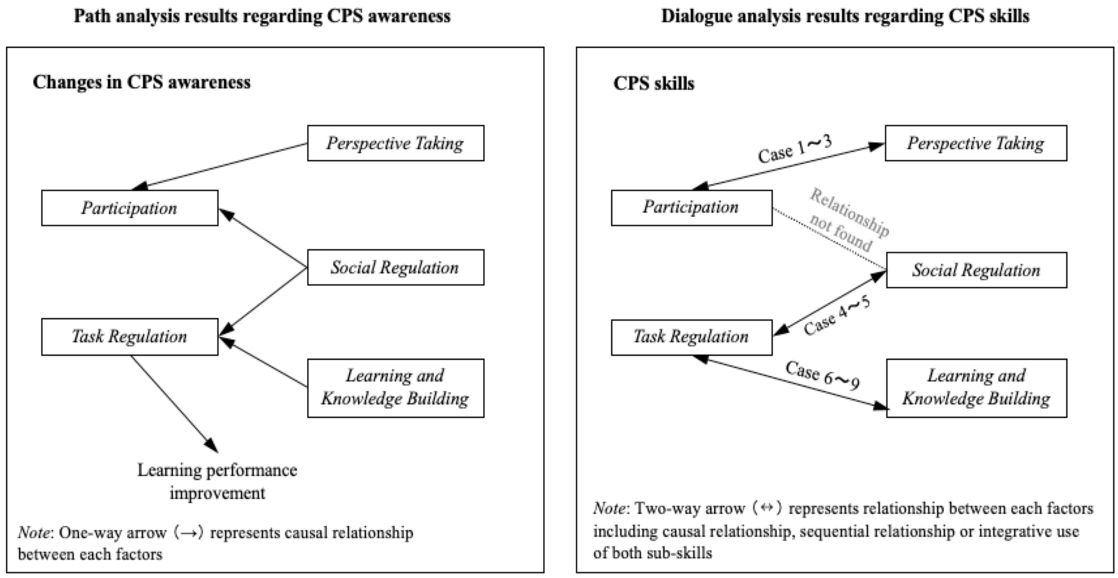


Figure 15. The results of the path analysis and dialogue analysis regarding CPS

5.3.7.2 Other relationships between CPS sub-skills in addition to path analysis results

According to the results in 5.3.7.1, compared with the path analysis results, which showed a simple one-way relationship between each CPS factor, the results of dialogue analysis indicated the mutual effects of using CPS skills during students' group work. In this subsection, other relationships between CPS sub-skills in addition to path analysis results were analyzed to examine the complete relationships between all CPS skills use. The relationships were found between *Task Regulation* and *Participation*, *Perspective Taking* and *Task Regulation*, *Social Regulation* and *Perspective Taking*, *Social Regulation* and *Learning and Knowledge Building*, *Perspective Taking* and *Learning and Knowledge Building.*

(1) *Task Regulation* and *Participation*

Two cases were identified that showed the relationships between *Participation* and *Task Regulation*, including one-way relationship and mutual relationships, respectively. Case 10 is in the (a) *Use of acid and alkali* topic, and Case 11 is in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 10 (Group 8, Class 3) *Participation → Task Regulation*		
	111. S1: Let's see the next example. See, we can drink soda water when you have a	This case shows a conversation in which one student has conducted interaction with the other one to help that

	stomachache.	student understand the knowledge, and then when they have encountered the challenge that they could not solve, they chose to search for information on the Internet.
Interaction (*Participation*)	112. S2: Let me ask you a question. 113. S1: Go head. 114. S2: Is stomach medicine acidic or alkaline? 115. S1: Alkaline. 116. S2: Why is it alkaline? 117. S1: Because the gastric juice is acidic. 118. S2: Yes, and see, this is very important.	In Lines 112~118, S2 asked S1 about the acid-base property of stomach medicine and further requested S1's reason for S1's answer. In Line 117, S1 showed his agreement to the answer and why he asked the question. Therefore, it can be inferred here that S2 has already known the related knowledge and asked this question in order to confirm S2 was having the same knowledge. This conversation can be seen as an active interaction action to improve the understanding of knowledge by questions.
	119. S1: Lime, sprinkle it in the soil. It can improve the soil quality. 120. S2: That's right. 121. S1: Any other examples? Let me think about it. 122. S2: Is lime acidic or alkaline? Is this acidic or alkaline? 123. S1: Let me take a look. 124. S2: Acidic.	In Lines 125~128, when S1 and S2 tried to explore more related examples beyond their prior knowledge, they used the Internet as a tool to search for necessary information.
Collects elements of information (*Task Regulation*)	125. S1:Do you know other examples? Let's search it on Baidu. 126. S2: Examples of neutralization. 127. S1: (Searching for information.) Examples of neutralization. 128. S1: Here, there is the example of the wasp.	In this case, students used different skills according to their different purposes and prior knowledge. They used Interaction (*Participation*) skill to help improve the knowledge understanding, and used Collects elements information (*Task Regulation*) to collect necessary information when they could not solve the problem with their prior knowledge.

<table>
<tr><th colspan="3">Case 11 (Group 1, Class 1)
Task Regulation ↔ Participation</th></tr>
<tr>
<td>Resource management (Task Regulation)

Interaction (Participation)

Collects elements of information (Task Regulation)</td>
<td>27. S3: You open the 1, I open the 2.
28. S1: The preview 1 (learning material)? I open the preview 1, you open the second one, right?
29. S3: Yes, and now we read this material first.
30. S1: Wait a minute. Let me turn to that page, and I need to look for the information.
31. S3: Ok.
32. S1: Let me find the information for you.
33. S3: Yes, then show this page on the screen, and let's discuss.
34. S1: I found it for you. Look, here (content of the textbook).
35. S3: Great.
36. S1: (Read the content of the textbook.) At the bottom of Lake Nyos, a large number of magma deposits have accumulated.
37. S3: So, so it killed people.
38. S1: But it didn't kill people. Look at here.
39. S3: It is carbon dioxide poisoning.
40. S1: But it didn't kill people. Look at here. It only killed animals, here. It only killed animals, right? Look at here. It only killed animals.
41. S3: It also killed people, and it was because of carbon dioxide</td>
<td>This case shows a conversation in which students manage the provided learning materials through interaction within the group. After that, they found the related information with the problem in the learning materials and analyzed the elements of the problem by the communication.
In Lines 27~34, S1 and S3 conducted a simple discussion to decide how to open the provided learning materials to find the related information related to the use of Resource management skill. In this activity, they did not just divide the labor to open the learning materials, but also discussed how to display the learning materials, ensure the readability of the information, and help each other to find the necessary information (in Line 32~34), which was related to the use of Interaction skill.
In Lines 40~41, after managing the available resource, S1 found the inconsistency of one element of the problem (the problem described that the lake killed people) with the information in the learning material (S1 only found the information about the animals). S3 recognized S1's wrong understanding of the point of the problem as well as the provided information so that S3 corrected S1's viewpoint and understanding.
In this case, students first used Task</td>
</tr>
</table>

	poisoning.	*Regulation* skill and *Participation* skill to decide how to manage the available materials for problem-solving within the group. After that, students used Task Regulation skill to analyze and understand the information in the learning materials.

(2) *Perspective Taking* and *Task Regulation*

Two cases were identified that showed the relationships between *Perspective Taking* and *Task Regulation*. Case 12 is in the (c) *Limnic Eruption* topic and is presented as follows. Another case was presented in Case 9, showing that students were using *Task Regulation* skill and *Task Regulation* skill integratively to help accept and adapt to others' contributions.

Elements of sub-skills	Discussion	Description of the discussion
Case 12 (Group 6, Class 4) *Task Regulation → Perspective Taking*		
Collects elements of information (*Task Regulation*) Adaptive responsiveness (*Perspective Taking*)	75. S1: Look at this, page 7, 76. S2: This picture, right? 77. S1: Yes, look, this is a volcano, and the lava, the rock blocked the crater. Oh, I got it. See this rock, it blocked the crater, so the lake erupted suddenly. 78. S2: Oh, I got it, I got it. Carbon dioxide was released here, and then it was full of carbon dioxide gas.	This case shows a conversation in which one student first explained the information in the learning materials, and the other students accepted the explanation and made more contributions to the explanation based on the understanding. In Lines 75~77, S1 explained the mechanism of the Limnic Eruption based on analyzing the elements of the picture in the learning material, which was related to the *Collects elements of information* skill. In Line 78, S2 showed his understanding and acceptance of S1's explanation and explained the mechanism with more elements to help them understand the information better, which was related to the

		In this case, students first used *Task Regulation* skill to analyze and understand the elements of the provided information, and this activity helped them accept and respond to other's opinions and explanations (*Perspective Taking*).

(3) *Social Regulation* and *Perspective Taking*

Two cases were identified that showed the relationships between *Perspective Taking* and *Social Regulation*. The Case 13 is in the (a) *Use of acid and alkali* topic, and Case 14 is in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
	Case 13 (Group 1, Class 2) *Perspective Taking* → *Social Regulation*	
Adaptive responsiveness (*Perspective Taking*) Responsibility	25. S2: The examples of mixing acid and alkali solutions. 26. S3: Let me think about it. Let's search for that. What have you found? 27. S1: I don't know. 28. S3: Well, let's think about it. 29. S1: Oxalic acid, can be used to make clothes fade. 30. S3: That's a good example. Go on. 31. S1: Sulfuric acid, can be diluted with ammonia in industry. 32. S3: Yes, yes, our S1 (the name of S1) got good answers. Any other examples? 33. S2: Acid-base solution. Did you write this in reverse? 34. S3: (Summarizing the	This case shows a conversation in which students used the Adaptive responsiveness skill in *Perspective Taking* and Responsibility initiative skill in *Social Regulation* to solve the problem within the group. In Lines 29~32, S3 used supportive words to encourage S1 to think about the problem and provide more solutions related to the Adaptive responsiveness skill. After the discussion, in Line 34, S3 summarized the results of their discussion and took a memo for the following group presentation. In this case, students used supportive words to agree with other's contributions by using *Perspective Taking* skill, and then took the group responsibility as their own to summarize the results of the

initiative (*Social Regulation*)	<u>discussion) Oxalic acid can make clothes fade, oh decolorize. Hydrochloric acid can wash the stains on the toilet bowl.</u>	discussion for the group by using *Social Regulation* skill.
Case 14 (Group 4, Class 3) *Learning and Knowledge Building* ↔ *Social Regulation* → *Perspective Taking*		
Negotiation (*Social Regulation*) Relationships (*Learning and Knowledge Building*) Adaptive responsiveness (*Perspective Taking*)	214. S1: Carbon dioxide is toxic, isn't it? 215. S2: How can carbon dioxide be toxic? 216. S3: Carbon dioxide is toxic. <u>217. S2: Do you drink carbonated drinks? Isn't there carbon dioxide in that?</u> <u>218. S3: Oh yes.</u> <u>219. S1: So carbon dioxide is not toxic, right?</u> <u>220. S2: It's not toxic. There is also carbon dioxide in Cola, and are you poisoned when you drink Cola?</u> 221. S1&S3: (Laughter) 222. S1: I got it. <u>223. S3: Yes, I see, there is carbon dioxide in the drink, because it's called carbonated drink, carbonated drink.</u>	This case showed how students conducted negotiation and used *Learning and Knowledge Building* skill to reach an agreement, and students showed their acceptance and adaptation to others' contributions. In Lines 217~220, students conducted a negotiation about whether the carbon dioxide is toxic or not. In order to persuade others, S2 used the familiar example in their daily life to explain why he thought carbon dioxide is not toxic, which was related to Relationships skill. In Lines 221~222, S1 and S3 showed their acceptance of S2's explanation, which showed that the group had reached an agreement. Moreover, in Line 223, S3 emphasized his acceptance and provided some supplementary explanation about the understanding of the carbonated drink, which was related to the Adaptive responsiveness skill. In this case, students used *Learning and Knowledge Building* skill to understand the unfamiliar knowledge during the negotiation, and used *Perspective Taking* skill to show their acceptance and adaptation to others'

		contributions when the negotiation had reached an agreement.

(4) *Learning and Knowledge Building* and *Social Regulation*

One case was identified to show the relationships between *Learning and Knowledge Building* and *Social Regulation*, which was showed as Case 14. In this case, *Learning and Knowledge Building* skill was used by students as a tool to help understand the unfamiliar knowledge and reach the agreement during the negotiation within the group.

(5) *Learning and Knowledge Building* and *Perspective Taking*

Three cases were identified to show the relationships between *Learning and Knowledge Building* and *Perspective Taking*. The first case was shown in Case 9, in which *Learning and Knowledge Building* skill was used as a tool to understand the unfamiliar knowledge, and *Perspective Taking* skill was used to accept and adapt others' contributions. The second case was showed in Case 14, in which *Learning and Knowledge Building* skill was also used as a tool to understand the unfamiliar knowledge during a negotiation, and *Perspective Taking* skill was used to show their acceptance and adaptation to others' contributions when the negotiation had reached an agreement.

The third case is showed as following, which is in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 15 (Group 1, Class 4) *Learning and Knowledge Building* → *Perspective Taking*		
Relationships (*Learning and Knowledge Building*)	9. S1: You see, first, the carbon dioxide is definitely soluble in water. 10. S2: (Saying at the same time) soluble in water. 11. S1: Yes, like the Cola we drink, (carbon dioxide) is soluble in water, right? 12. S2: Exactly. 13. S1: Yes, then in this, carbonic acid solution, this carbon dioxide is a solute, right? 14. S2: Solute.	In this case, two lower performers conducted a discussion to understand the definition of solute, solvent, and solution. In Line 11, S1 used Relationships skill to connect the current knowledge with their familiar example. As one feature of this group, Adaptive responsiveness skill was frequently used during their discussion, especially S1. For example, in Lines 11, 13, 17, 21, 25, and 27, S1 always said 'Yes' or 'Right' to show the agreement of S2's explanations. Another feature was that both S1 and

Adaptive responsiveness (*Perspective Taking*)	15. S1: Solute, it should be solute. 16. S2: It is called the solute. 17. S1: Yes, it is the solute. 18. S2: So, what is the substance that dissolves carbon dioxide? 19. S1: I think it is… 20. S2: It should be water. 21. S1: Yes, carbon dioxide, the substance that dissolves carbon dioxide, is water. Then it becomes carbonic acid solution, right? Then, then, carbon dioxide, is called… 22. S2: Solute? 23. S1: Not solvent? 24. S2: Solvent, solvent. 25. S1: Right. 26. S2: It is called a solute, and carbon dioxide is a solute. 27. S1: Yes, solute.	S2 tended to repeat each others' words. For example, in Lines 13~17, S1 and S2 repeated the same word 'solute' several times, without detailed descriptions or explanations. Therefore, although they showed a positive response to others' contributions, it was considered not helpful in understanding the meaning of the words. Similarly, in Line 20 and 21, 26 and 27, the words 'water' and 'solute' were repeated, respectively, but not indicated the effectiveness in understanding or constructing knowledge. In this case, students used *Learning and Knowledge Building* skill to connect the current problem with their familiar knowledge, and positively used *Perspective Taking* skill to show acceptance and agreement to each others7 contributions. However, this case is considered ineffective in constructing knowledge since most of the dialogue repeated the words without supplementary description or further explanation of the definition.

According to the above results, relationships between each CPS sub-skills were identified, indicating that students used several CPS sub-skills as a set, or used CPS skills integratively rather than used CPS skills separately.

In Case 10, students used Interaction in *Participation* skill to help improve the knowledge understanding, and used Collects elements information in *Task Regulation* skill to collect necessary information when they could not solve the problem with their prior knowledge.

In Case 11, students first used *Task Regulation* skill and *Participation* skill to decide how to manage the available materials for problem-solving within the group. After that, students used *Task Regulation* skill to analyze and understand the information in the learning materials.

In Case 12, students first used *Task Regulation* skill to analyze and understand the elements of the provided information, and this activity helped them accept and respond to other's opinions and explanations (*Perspective Taking*).

In Case 13, students used supportive words to agree with other's contributions by using *Perspective Taking* skill, and then took the group responsibility as their own to summarize the results of the discussion for the group by using *Social Regulation* skill.

In Case 14, students used *Learning and Knowledge Building* skill to understand the unfamiliar knowledge during the negotiation, and used *Perspective Taking* skill to show their acceptance and adaptation to others' contributions when the negotiation had reached an agreement.

In Case 15, students used *Learning and Knowledge Building* skill to connect the current problem with their familiar knowledge, and positively used *Perspective Taking* skill to show acceptance and agreement to each others' contributions. However, this case is considered ineffective in constructing knowledge since most of the dialogue repeated the words without supplementary description or further explanation of the definition.

The results of this subsection were integrated with the results in 5.2.7.2 and showed in Figure 16.

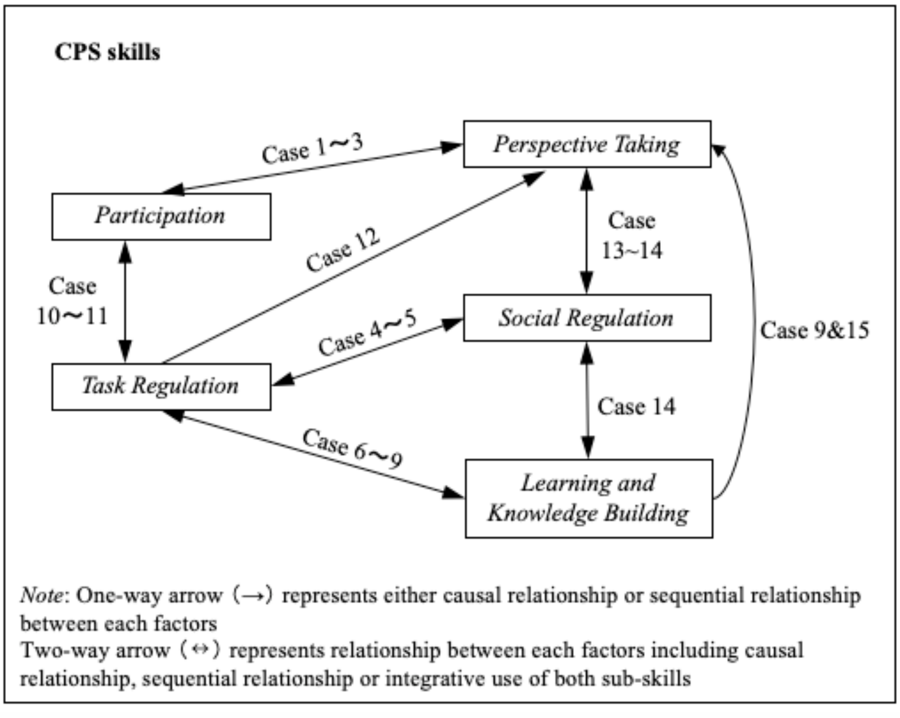


Figure 16. Relationships between all CPS sub-skills

5.3.7.3 Differences in the use of CPS skills among high and low learning performance groups

According to the dialogue analysis, it is found that students showed different levels of contributions for the groups, as well as the understanding of the knowledge for their own. Considering the different effects of students' prior knowledge level (RQ6-e), it is assumed that students with different levels of prior knowledge and skills would make various contributions to the groups. Therefore, I identified the prior knowledge level of each student in different groups to examine the different patterns of using CPS skills in different groups.

In RQ6-f, students were divided into two groups, high-performance (N = 21, Mean = 39.14) and low-performance (N = 28, Mean = 11.57) groups. Students in high-performance group are identified as H, while those in low-performance group are identified as L. The rest of them are identified as M. I have examined the patterns of using CPS skills in the different grouping, which is All H (students in this group are all high performers), All M (students in this group are neither high performers nor low performers), All L (students in this group are all Low performers), HML (the group consists of three kinds of students).

(1) All H group type

In this type of group, three patterns of the use of CPS skills are identified:

1. *Task Regulation* only
2. *Task Regulation* → Using BookRoll tools
3. *Task Regulation* → *Learning and Knowledge Building* → Using BookRoll tools

First, one noticeable feature is that All H groups tended to use cognitive skills in CPS, especially *Task Regulation* skill, to manage the labor and the available and necessary information. They also tended to use some cognitive tools to helps them understand the contents and related knowledge. One example of 3. *Task Regulation* → *Learning and Knowledge Building* → Using BookRoll tools pattern is presented as follows. This example is in the (c) *Limnic Eruption* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 16 (Group 8, Class 2) *Task Regulation* → *Learning and Knowledge Building* → Using BookRoll tools		
Resource management (*Task Regulation*)	259. S2: Look, you can open the second learning material. It is the other one of what S1 has opened. Isn't it? Isn't it? 260. S3: Yes. 261. S2: Where is it? 262. S1: Come on, help me. 263. S2: How about let S3 open the second learning material? I	In this case, three high performers conducted a discussion about the Limnic Eruption topic. First, in Lines 259~265, they discussed how to manage the provided learning materials within the group, related to the use of Resource management skill. In Lines 280~283, after reading the relevant materials, S2 remembered one

	will open the preview material. 264. S1: I have opened it. 265. Mine is the preview material. …	familiar example in daily lift, and S2 connected this example with the current problem they were tackling to help others understand the knowledge and principle in an easier way.
Relationships (*Learning and Knowledge Building*)	280. S2: It's like one experiment my science teacher has shown us before. Put some mentos (candy) in the Cola. 281. S3: Did the bottle explode? 282. S2: No, just spurted out. The teacher said that was the carbon dioxide gas was released. The teacher has put ten mentos into 1 liter of Cola. 283. S3: Maybe you should put ten packs of mentos. …	In Lines 286~290, S1 took the memo about the discussion results, and S2 and S2 gave S1 some help about how to use BookRoll tools. In this case, high-performance students used some skills of *Task Regulation* to identify the cognitive skills to understand the contents and knowledge by managing the available labor and information. Then they tended to use some cognitive tools such as memos to help the understanding.
Add memo (Using BookRoll tools)	286. S1: We need to take a memo. Should I open this window again? But I have already opened it once. 287. S2: You don't need to do that. Now press Enter, the Enter button, yes, press. 288. S3: It's Ok even not press the Enter. 289. S2: But that would be faster. 290. S1: Yes, I pressed, and I have saved the memo.	

(2) All M group type

In this type of group, seven patterns of the use of CPS skills are identified:

1. *Social Regulation* only
2. *Perspective Taking* ↔ *Participation* (Case 3)

3. *Social Regulation* → *Task Regulation* (Case 4)
4. *Task Regulation* only
5. *Task Regulation* → *Learning and Knowledge Building* (Case 7)
6. Using *Task Regulation & Perspective Taking* respectively
7. Using BookRoll tools → *Task Regulation*

Unlike the All H group type, this group type showed more various patterns of using CPS skills, including cognitive and social skills in CPS. The patterns 2, 3, and 5 were showed in Case 3, 4, and 6, respectively. Pattern 1 showed students' use of negotiation of *Social Regulation* to reach an agreement about whether the CO_2 is poisonous or not. Pattern 4 showed students' use of *Task Regulation*, including Resource management and Collects elements of information, to understand the contents and knowledge about the topic.

Examples of 6. Using *Task Regulation & Perspective Taking* respectively and 7. *Task Regulation* → Using BookRoll tools patterns are presented as following. This example is in the (a) *Use of acid and alkali solutions* topic.

Elements of sub-skills	Discussion	Description of the discussion
Case 17 (Group 7, Class 3) Using *Task Regulation & Perspective Taking* respectively		
Problem analysis (*Task Regulation*)	76. S1: If you are stung by a bee, you can be stung by a wasp again. 77. S2: No, why? 78. S1: The wasp (means wasp venom) is alkaline, right? So we should use acid for disinfection, right? If you let the bees sting you again, wouldn't it be acidic? The problem would be solved. 79. S2: You are so imaginative. …	In this case, three middle performers conducted a discussion about the possible measures after being stung by a bee. First, in Lines 76~79, S1 identified the points of the problem as the acidic and alkaline of the bee venom, and S1 proposed a solution by using the alkaline substance to the bee venom. Although S1's solution is not executable, the points of the problem and the direction of the solution are correct.
Adaptive responsiveness	102. S2: About the neutralization. 103. S1: I know this. It's acidic and alkaline. If you are stung by something acidic, you can use alkaline to disinfect it. If you	In Lines 102~107, students were continuing the topic of bee venom. However, they changed the viewpoint of the problem, which was how to neutralize the solution. First, S1 described the method to neutralize the solution (Line 103), S3 and S4 described the additional

(*Perspective Taking*)	mix it together, will it become neutral? 104. S3: But if the acidity is too high or the alkalinity is too low. . . 105. S4: It doesn't work. 106. S3: If the alkalinity is too high and the acidity is too low, it will become alkaline instead of neutral. So you should find a point that is just neutral. 107. S1: I think this acid-base solution is so interesting.	information for the neutralization, based on the acceptance of S1's contribution (Lines 104~106). In this case, three middle-performance students used Problem analysis (*Task Regulation*) skill to analyze the problem, and Adaptive responsiveness (*Perspective Taking*) to help construct knowledge and understanding of the group. I identified this case as Using *Task Regulation & Perspective Taking* respectively because when students were discussing neutralization, they did not conclude some findings during the former discussion, which can be used in the later discussion.
Case 18 (Group 5, Class 3) Using BookRoll tools → *Task Regulation*		
Add marker (Using BookRoll tools) Collects elements of information (*Task Regulation*)	53: S1: Let's highlight this content. 54. S2: Use the red marker. It means you don't understand well. 55. S1: Ok, Ok. So is the stomach medicine mainly acidic or alkaline? 56. S2: Alkaline. 57. S1: I think it is alkaline too. Let me check. (Searching for the information) Yes, alkaline.	This case showed a short dialogue between two middle performers about how they used BookRoll tools to help collect and analyze the information. First, in Lines 53~54, S1 tried to highlight the contents he did not understand well by using marker tools of the BookRoll system. However, S2 told S1 the inappropriate use of red and yellow markers (red: important, yellow: not understand well). This is one possible reason that there are no significant differences between the use of different markers. In Lines 55~57, S1 and S2 discussed the contents they do not understand, and S1 searched for further information to confirm their answer, which is related to

		the use of Collects elements of information skill. In this case, students used BookRoll tools to highlight the contents they did not understand well, shared the highlighted contents and then used *Task Regulation* skill to analyze these contents.

(3) All L group type

In this type of group, few meaningful discussion (discussing the problems) was conducted. Most the students in these groups were talking about other irrelevant topics. Only one pattern of using CPS skills is identified: *Learning and Knowledge Building → Perspective Taking*, which is shown in Case 15.

(4) HML group type

In this type of group, six patterns of the use of CPS skills are identified:

1. *Social Regulation* only
2. *Task Regulation* only
3. *Task Regulation ↔ Social Regulation* (Case 5)
4. *Task Regulation → Learning and Knowledge Building* (Case 6)
5. *Perspective Taking → Task Regulation → Social Regulation*
6. Using BookRoll tools → *Task Regulation*

This group type also showed various patterns of using CPS skills, including cognitive and social skills in CPS, the same as the All M group type. Pattern 3 and 4 were shown in Case 5 and 6, respectively. Pattern 1 showed students' use of negotiation of *Social Regulation* to reach an agreement about whether the CO_2 is poisonous or not. Pattern 2 showed students' use of *Task Regulation* including Problem analysis, and Collects elements of information, to understand the contents and knowledge about the topic.

Examples of 6. *Perspective Taking → Task Regulation → Social Regulation* and 7. Using BookRoll tools → *Task Regulation* patterns are presented as following. This example is in the (a) *Use of acid_and alkali solutions* topic.

Elements of sub-skills	Discussion	Description of the discussion

<table>
<tr><td colspan="3">Case 19 (Group 2, Class 3)
Perspective Taking → Task Regulation → Social Regulation</td></tr>
<tr><td>Adaptive responsiveness (*Perspective Taking*)

Resource management (*Task Regulation*)

Negotiation (*Social Regulation*)</td><td><u>6. S2: When acid and alkali are put together, it will become neutral, right?</u>
<u>7. S1: It depends on your quality and ratio.</u>
<u>8. S2: If the ratio is the same, it is neutral.</u>
9: S1: Yes, and then let me tell you, the formic acid, must be an acidic solution. So we can apply some alkaline solution to make it neutral.

<u>10. S2: Let me check it on the book. (Mouse sound, searching for information.)</u>

<u>11. S1: So is the stomach medicine acidic?</u>
<u>12. S2: Yes.</u>
<u>13. S3: I think it's alkaline.</u>
<u>14. S1: Why?</u>
<u>15: S3: Because our gastric juice is acidic.</u>
<u>16. S2: So the stomach medicine is also acidic.</u>
<u>17. S3: No, we should make it neutral, so it's alkaline.</u>
<u>18. S2: Oh, I see.</u></td><td>In this case, three middle performers conducted a discussion by using the social skills and cognitive skills to solve the problem.
First, in Lines 6~7, S2 tried to understand the knowledge about neutralization, and S1 explained the point of the neutralization. In Line 8, S2 responded to S1's contribution and indicated the understanding of the knowledge.
In Line 10, regarding the contribution from S1, S2 chose to search for more information to check S1's contribution.
In Lines 11~18, based on the above understanding of knowledge, three students conducted a negotiation about whether stomach medicine is alkaline or not. At first, S2 and S3 hold different opinions (in Line 12~13), then S3 explained the reason based on the knowledge of neutralization they have discussed previously.
In this case, students used social skills and cognitive skills, including *Perspective Taking* and *Task Regulation*, to improve the understanding of the knowledge, and finally used conducted negotiation by using *Social Regulation* skill to reach an agreement within the group.</td></tr>
<tr><td colspan="3">Case 20 (Group 4, Class 1)
Using BookRoll tools → *Task Regulation*</td></tr>
<tr><td>Add markers</td><td><u>129. S1: These are what I</u></td><td>The case shows how students use</td></tr>
</table>

(Using BookRoll tools) Collects elements of information (*Task Regulation*)	highlighted. I used the red color. 130. S2: Suffocation, what is it? 131: S1: I don't know. 132. S3: There is a website. 133. S1: Which one? 134. S3: The second one, we should check it. 135. S1: I can't read it. 136. S2: It is Japanese. 137. S1: I will search for the killing lake.	BookRoll tools and the use of CPS skills. In Line 129, S1 highlighted the contents of the learning materials and shared the contents with others. The group conducted a short discussion about the contents they did not understand commonly. In Lines 132~137, to understand the contents, this group chose to search for additional information on the Internet. In this case, students used BookRoll tools and the *Task Regulation* skill to understand the contents.

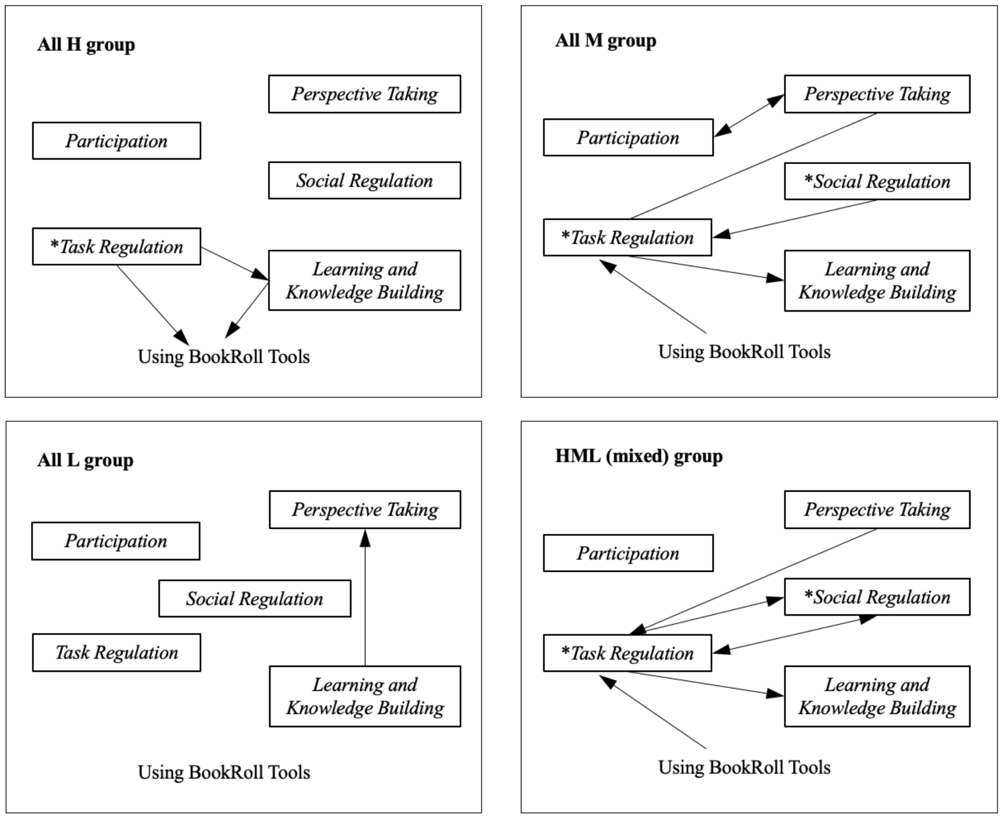
From the results above, the different patterns of using CPS skills among different group types are identified, indicating the influence of students' prior knowledge and skills on their use of CPS skills. From the results, in the All H groups, in which the group members have more prior knowledge, students tended to use cognitive skills in CPS, especially *Task Regulation* skill, to manage the labor and the available and necessary information, rather than social skills. It is estimated that when students have enough knowledge or skills to solve the problem on their own, they rely less on others during collaboration. It is one of the limitations in this study. In future work, it is necessary to set the various level of the problems for students and examine whether these students would use social skills when the problems to be solved are beyond their knowledge and skills.

As for those students who do not have enough prior knowledge, first, the All M group type and Mixed group type show more patterns of using the CPS skills, including using cognitive skills or social skills respectively or using both dimensions integratively. It is indicated that heterogeneous group with different levels of prior knowledge can promote using both dimensions of CPS skills.

In All L group, most students talked about irrelevant topics, and only one pattern of using CPS skills was identified. It is indicated that if students in one group lack enough knowledge and skills, their cognitive and social activities may be limited. Some supports and scaffolding should be provided, or the grouping of such type should be reconsidered.

Concerning the learning behaviors of using BookRoll tools, it is found that All H groups tended to use cognitive skills to understand the problem and knowledge, then use BookRoll tools to highlight or summarize the contents. In All M group types and Mixed groups, students tended to use the BookRoll tools to highlight the contents and share this information with other members, then understand the problem and knowledge through the collaboration.

The patterns of using CPS skills of four group types are presented in Figure 17.



Note:
One-way arrow (→) represents causal relationship or sequential relationship between each factors
Two-way arrow (↔) represents mutual relationship between each factors or using each CPS skills repeatedly
Line (—) represents the use of both skills in one discussion without mutual relationship
Symbol of * represents the use of this skill only in one discussion

Figure 17. The patterns of using CPS skill of four group types

5.4 Conclusion

In this experiment, CPS-based STEM lessons were designed for seventh-grade students following the CPS process framework and STEM integration. The effectiveness of the practical experiments was examined from two aspects, the CPS design, and the STEM learning outcomes.

Regarding the effectiveness of CPS design, first, the changes in CPS awareness before and after the lessons were examined, and significant improvements of CPS awareness were found, indicating the effectiveness of the design.

In order to figure out what factors and how these factors affected the improvements of learning performance and CPS awareness, the causal relationships between the use of STEM learning strategy, learning behaviors, CPS awareness, and learning performance were examined. The path analysis results showed the direct effects of changes in *Task Regulation* awareness in CPS and specific factors in learning behaviors on learning performance improvement. As for the use of

STEM learning strategy, some factors affected learning performance improvement, mediated by some CPS factors. The path analysis results indicated that these factors should be considered for the CPS-based STEM design.

In addition, effective learning behaviors were identified, which improve learning performance in different learning phases, based on the causal relationships of learning behaviors and learning performance and the connections between learning behaviors and learning strategy.

Some previous studies regarding CPS-based STEM education provided insights into designing or assessing the CPS approach, which focused on one dimension of CPS or the integration of CPS, based on the STEM contents. In addition to the factors of CPS, this study provided evidence concerning what influential factors of STEM learning strategies and learning behaviors related to students' learning processes should be integrated into the CPS-based STEM design.

Regarding the STEM learning outcomes, the aim was to acquire related knowledge and apply the knowledge to authentic problem-solving. The outcomes concerning this aim were assessed through the final presentations, tests, and dialogue analysis. First, students acquired and constructed related knowledge through the lectures and group discussion and solved problems by reaching an agreement within the groups. The teachers assessed all the groups' solutions during the presentations and revised the knowledge by pointing out the discrepancies between the final solution and their reasons. For example, in the case of the acid rain, when students judging whether the news was true or false, they needed to grasp the critical elements of the news, such as the pH value of the acid rain, and the phenomena or the diseases which the acid rain may cause. However, some groups could not understand the main point of the problem and claimed that the news was false because they thought the volcanic ash could not reach the height mentioned in the news, but not provided any evidence or plan to prove their opinion. Therefore, the teacher commented on their presentations, provided practical suggestions to examine their opinions, and summarized the correct ideas from all the presentations at the end.

Second, pre-post tests were conducted to examine the acquisition and application of the related knowledge. It was found that the learning performance was significantly improved after the STEM lessons. In order to understand students' learning processes during the course and identify what factors would affect learning performance in different learning phases, path analysis was conducted to examine the causal relationships among learning behaviors, prior knowledge, and learning performance in three learning phases. As the results, in the *Learning and practice* phase, the behavior of turning to previous pages as a simple rehearsal strategy (reading learning materials repeatedly) was considered effective. However, the behavior of deleting red markers as metacognitive strategy such as reflection was found to negatively affect learning performance. In the *Reinforcement* phase, the behavior of deleting annotations regarding the reflection strategy was considered effective. The behavior of adding annotations regarding cognitive strategies reveals indirect effects on learning performance, mediated by deleting annotation behavior. In the *Application* phase, the behavior of jumping to specific pages regarding cognitive strategy was considered effective. From the above results, students' use of reading strategies and the prior knowledge of the previous phase affected the acquisition of new knowledge.

Finally, to examine how students used their CPS skills to construct knowledge, students' utterances and actions during the group work were analyzed by the dialogue analysis. In this instructional practice, the results of path analysis were first compared with the results of the dialogue analysis. It is indicated that although the results of path analysis showed the causal relationship between each factor of CPS awareness, actually when students used CPS skills during group work, the use of CPS skills showed mutual effects on each other, rather than a simple one-way relationship. Moreover, to examine the effects of the individual differences, the different patterns of using CPS skills among different group types are identified, indicating the influence of students' level of prior knowledge and skills on their use of CPS skills. For example, students with more prior knowledge tended to use cognitive skills in group work rather than rely on others' contributions. As for students who do not have enough prior knowledge, if they could collaborate with other high performers, they tended to use both dimensions or the integration of CPS skills in those heterogeneous groups.

In addition, considering the effects of individual differences on the final learning outcomes, the different effects of individual learning activities and group works and the level of prior knowledge were examined. Concerning the different effects of individual learning activities and group works, the learning behaviors of using marker tools during individual learning showed positive effects on the improvement of CPS awareness, which indicated the effectiveness of the individual thinking. As for the effects of prior knowledge, the low performers, who were with a lower level of prior knowledge, showed more connections between the use of STEM learning strategies and the CPS awareness, while in the high performers, the use of cognitive tools such as memo could help the development of social awareness for those who had a higher level of prior knowledge.

5.5 Limitations and future work

There are several limitations to this research. First, the duration of this study was only one month due to the limited condition of the experiment school. Thus, future research should extend the duration of the experiment. Moreover, to utilize technology to support the school learning environment, it is necessary to prepare sufficient time and opportunity for students to accept and be familiar with the new technology.

Moreover, in this study, I only collected learning logs of reading digital learning materials on the BookRoll system. In order to understand students' collaborative, cognitive, and metacognitive processes, it is necessary to collect more types of learning logs from other types of learning support systems or learning materials, covering more learning processes.

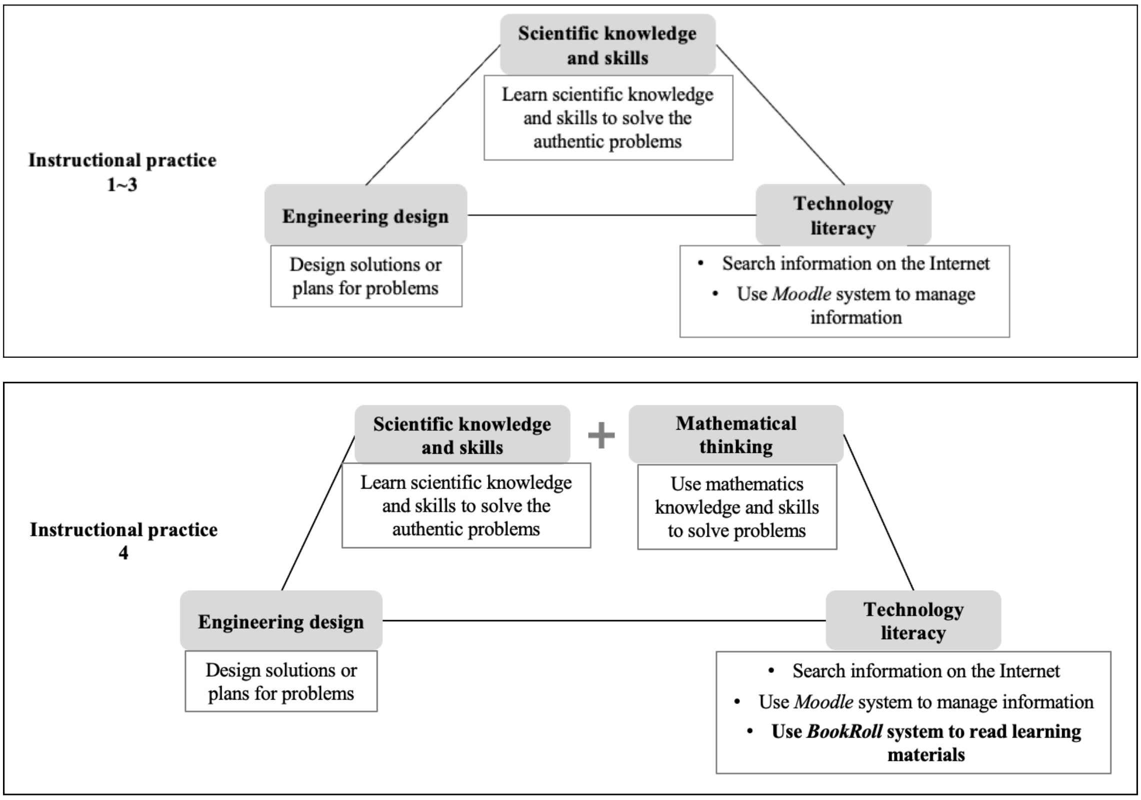
In future work, to construct a practical CPS process framework in the context of STEM, it is necessary to expand the sample size, increase the duration of the experiment, and integrate the critical factors into the design based on the current results. In addition, further experiments should be conducted to examine the effectiveness of the CPS-based STEM design.

Chapter 6: Conclusion

6.1 Instructional design of CPS-based STEM education

6.1.1 Integration of four STEM fields

This research designed CPS-based science and STEM lessons to improve students' CPS awareness and skills and learning performance. Science was used as the main domain context, and integrated with other three STEM fields. The design of each instructional practice regarding STEM fields is summarized and presented in Figure 18.



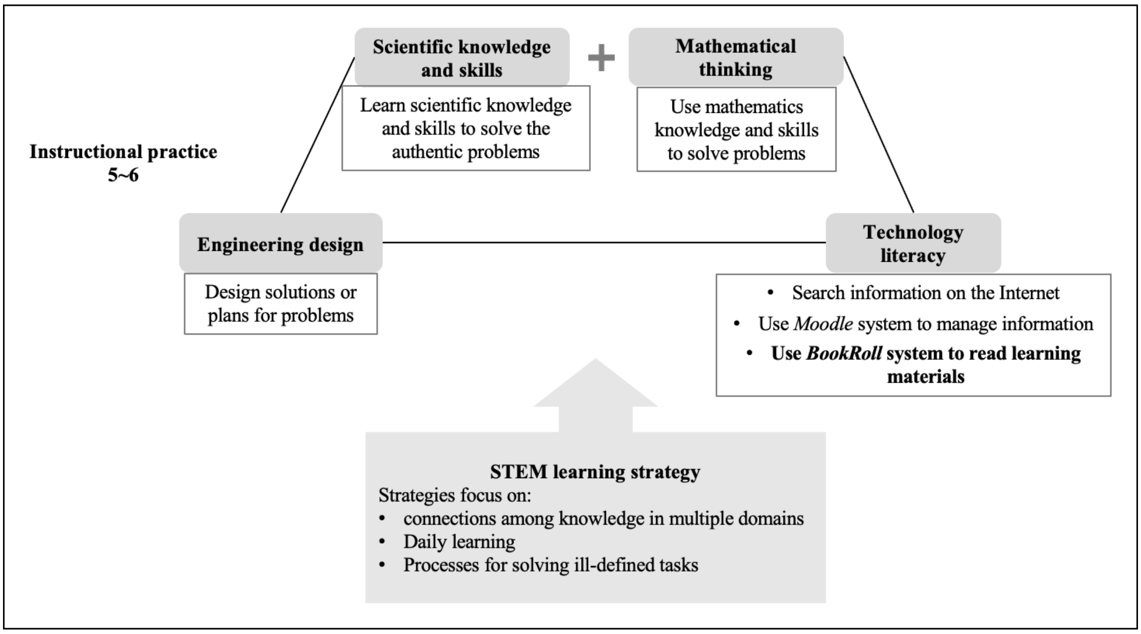


Figure 18. Design of each instructional practice regarding STEM fields

6.1.2 Learning activities in each STEM field based on the CPS processes

In STEM education, which incorporates Science (including natural science and humanities and social science), Technology, Engineering, and Mathematics, the problems in STEM always occur in real situations, and these problems are usually complex and ill-defined, which requires learners to share their knowledge and ideas with others, collaborate with others to find the solutions (Lou et al., 2011; Savery, 2006). Therefore, in STEM education, CPS skills are considered important to solve problems in STEM fields. Either in natural science or humanities and social science in STEM education, the goal of problem solving is to identify the problem and fill the gaps between the current situation and the expected situation of the problem, which means finding the solution. This goal should be accomplished through conducting authentic activities, including participating in real projects, or solving authentic or local problems and tasks in real life, and consider what contents are relevant to oneself, and reflect on the local implications (Herro et al., 2019; Wang et al., 2011). However, considering the difficulties in authentic experience for students to a specific project (Holmlund et al., 2018), in this study, the authentic situation was set from some global challenges including health, medical and environmental issues for students, and to make them reflect on their own lives through finding solutions for these problems.

The general STEM education incorporates knowledge and skills from multidisciplinary fields, including scientific inquiry, technology literacy, engineering design, and mathematical thinking (Kelley & Knowles, 2016). Considering the features of STEM education and the CPS approach, in this study, the STEM lessons were designed based on the integration of STEM fields, while the

CPS processes were considered in the design.

Specifically, in this study, science and mathematics are considered in the first three steps of CPS processes, *Identifying the problem*, *Representing the problem*, and *Planning and executing*. First, the problems are designed in authentic situations based on scientific content, which means that the problems need to be solved mainly by scientific knowledge and skills. As for the specific learning activities of science, students need to analyze the problem and understand the discrepancy between the current situation and the expected goal of the problem. During the group work, they need to represent this discrepancy more easily, such as using scientific symbols, figures, tables, or familiar words. Finally, they need to conduct scientific inquiry, including setting plans or hypotheses, executing the plans, or examining the hypotheses. Concerning the specific learning activities of mathematics, students can use mathematical symbols to represent the problems and understand the reasons and solutions by reasoning skills and logical thinking.

In the final step of CPS processes, *Monitoring and reflecting*, learning activities in Engineering are considered. Engineering design in CPS includes setting plans to problem solving based on the understanding of the elements of the problems, designing the specific solutions for the problems according to plans, and creating the solutions as the final products and evaluating the solutions. Finally, students need to revise their plans, designs, or methods for problem solving as necessary.

As for the Technology field, the technology is used as the tool in all steps of CPS processes to support the CPS processes and improve students' technology literacy. Students can use the computers to search the information on the Internet, to understand the problems, and use learning support systems to manage the available information and share the information with others. In addition, technology can be used to support students' cognitive learning activities, such as reading scientific learning materials while using functional tools. The learning activities regarding each STEM field based on the CPS processes are presented in Figure 19.

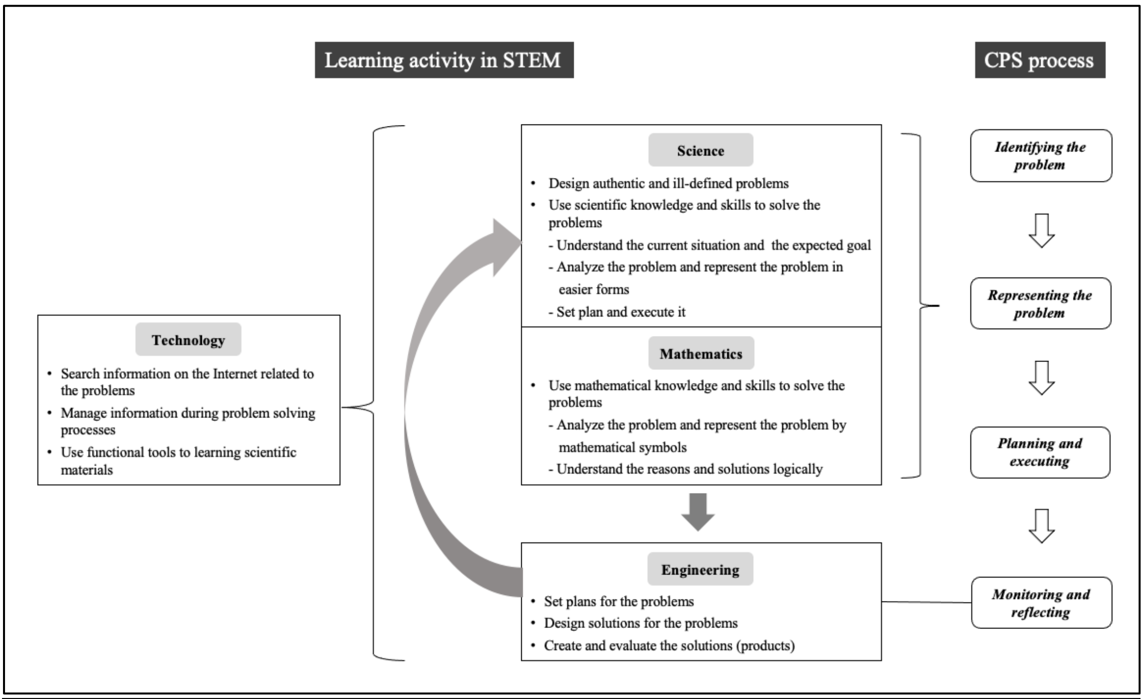


Figure 19. Learning activities regarding each STEM fields based on the CPS processes

6.1.3 Elements used in CPS-based STEM education designs

Behavioral factors were integrated into the CPS process design, based on the combination of learning performance data and psychological data. Therefore, the elements of the CPS-based STEM instructional design were identified, regarding the behavioral, psychological and strategic dimensions. The elements of the design of science and STEM lessons were summarized in **Table 17**.

Table 17 Elements of instructional designs

	Chapter 3				**Chapter 4**	**Chapter 5**
	Practice 1	**Practice 2**	**Practice 3**	**Practice 4**	**Practice 5**	**Practice 6**
CPS	C+PS	CPS process			Revised CPS process	
Learning behavior	×	×	×	Instructions for marker tools	Instructions for more cognitive tools	Instructions for cognitive tools during individual learning & group work

Learning strategy	CS regarding CPS	CS & MS (monitoring)	CS & MS (monitoring & reflection)	SS & MS (monitoring & reflection)
	Note: CS: Cognitive strategy, MS: Metacognitive strategy, SS: STEM learning strategy			
Learning form	G		I (reading materials before discussion) + G	I (preview & review) + G
	Note: I: Individual learning, G: Group work			

6.1.4 Prerequisites of designing CPS-based STEM lessons

To ensure that the CPS-based STEM learning can be conducted smoothly and successfully, two prerequisites, *prior knowledge and experience* and *group composition*, are considered important for designing lessons.

According to the framework of PISA 2015 (OECD, 2017), in addition to the core factors (collaboration and problem solving), student background is considered as an important factor for CPS. Student background for CPS learning includes students' prior knowledge of multiple fields such as mathematics, reading and writing, science, and society, and students' attitudes, experience, and motivation.

In this study, students' prior knowledge was considered as one of the important prerequisites for students' CPS-based STEM learning, and the effects of their prior knowledge were examined in instructional practices 4～6.

In instructional practice 4, since the content was based on the real disaster, which was out of the textbook and relied on students' prior knowledge and experience, students' pre-test score showed effects on the improvement of CPS awareness and affected the role of the using strategies and behaviors during CPS-based STEM learning. For example, students with higher level of prior knowledge paid more attention to the cognitive domain, and specific learning behaviors showed effectiveness during problem solving processes. Contrarily, students with lower level of prior knowledge paid more attention to social domain and showed significant connection behaviors some specific learning behaviors with social awareness.

In instructional practice 5, due to the small sample of the participates, the effects of students' prior knowledge on CPS-based STEM learning were not examined.

In instructional practice 6, since the content was designed based on the textbooks mainly, and the knowledge in this course was brand new for students, students' pre-test score did not show effects on the improvement of learning performance or CPS awareness. However, compared with students with lower level of prior knowledge, those with higher level of prior knowledge showed significant relationships between the use of annotation tool with the improvement of social awareness in CPS. It is indicated that reviewing and reflecting on the annotations is effective during the collaborative process for students with higher level of prior knowledge.

Therefore, first, when designing CPS-based STEM, the level of students' prior knowledge and experience should be considered based on the contents. For example, if the content is based on the authentic event and out of the textbooks, it is necessary to provide students with the related information to help students acquire the necessary prior knowledge. Moreover, students with lower level of prior knowledge paid more attention to social process rather than cognitive process, and they hardly perceived the effectiveness to use the cognitive tools during cognitive process. Therefore, it is necessary to provide some guidance regarding how to use cognitive tools and strategies to understand knowledge, for students who lack prior knowledge.

In addition, according to the results of the dialogue analysis, the group composition regarding the level of prior knowledge showed the effects on the use of CPS skills. If all members in one group have enough prior knowledge to solve the current problems, they tend to use cognitive skills to solve the problem and confirm the solution with others, rather than collaborate with others. Contrarily, if all members in one group have insufficient prior knowledge to solve the current problems, they tend to use both cognitive skills and social skills ineffectively. Compared with these homogeneous groups, the heterogeneous groups, which are mixed with high performers, middle performers, tend to use both cognitive skills and social skills integratively.

Second, when designing CPS-based STEM, the formation of the group should also be considered. To improve the use of CPS skills during group works, it is effective to compose the groups with different levels of prior knowledge and learning proficiency. In these heterogeneous groups, students tend to use their available cognitive skills to analyze the discrepancy between the current situation and the expected goal of the problems and use social skills to share the cognitive findings and supplement the missing understanding for the contents.

6.2 Results and implications of instruction designs

The results of the instructional practices in each chapter are summarized in **Table 18**, including the important behavioral and strategic factors that should be considered in the design, the effects of these factors on the improvement in learning effectiveness (learning performance and CPS awareness or skills), and the data collection, based on the different learning forms. Some implications regarding the design and the development of the CPS-based STEM education are provided based on the conclusions.

Table 18 Results of CPS-based STEM instructional practices

Learning form	**Factors that should be considered**		**Learning effectiveness (learning performance & CPS)**	**Data collection**	**Chapter**
	Learning behavior	Learning strategy			
Lecture/group work	Delete marker	Reflection strategy (review the learning materials and reconsider the contents)	Delete marker is related to improvement of *Social Regulation* awareness	Questionnaire, learning log	3
Group work	Add marker Delete marker (using the marker tool to understand the contents, share and discuss the contents with group members)		Use of mark is related to improvement of learning performance	Performance test, learning log	4
Individual learning		Organization, Using reference		Questionnaire	4
Lecture (learning and practice)	Reading contents repeatedly		→ improvement of learning performance	Performance test, learning log	5

Lecture (reinforcement)	Add memo Delete memo	Reflection Organization, Elaboration and Attention	Add memo, Delete memo → improvement of learning performance	Performance test, questionnaire, learning log	5
Lecture (Application)	Page jump (searching for specific information)	Organization, Elaboration and Using reference	Page jump → improvement of learning performance	Performance test, questionnaire, learning log	5

According to the quantitative and qualitative analysis results in this study, the important behavioral and strategic factors were specialized and categorized into two main learning forms in CPS learning, individual learning and group work. The results are presented in Figure 20.

First, in the individual learning, which was conducted in *Identifying the problem* process in CPS, the behaviors of reading contents repeatedly and Page jump were found to have positive effects on the improvement in learning performance. This behavior of reading contents repeatedly was related with the passive rehearsal strategy and was effective in the basic learning and practice phase in CPS-based STEM learning. The behavior of Page jump, which means jumping to a specific page when searching for specific information, was related with the Organization strategy, Elaboration strategy, and Using Reference strategy.

In the group work, which was conducted in *Representing the problem*, *Planning and executing*, and *Monitoring and reflecting* processes in CPS, the use of marker tool was found positively related with the improvement of *Social Regulation* awareness in CPS and learning performance, and the use of memo tool positively affected the improvement of learning performance. The behaviors of adding markers or memos were related to the cognitive strategies such as organization and elaboration, strategies, and the behaviors of deleting markers or memos were related to the metacognitive strategy such as reflection.

Finally, according to the level of prior knowledge, the effects of different group compositions on the use of CPS skills were examined. Students with a lower level of prior knowledge tended to focus on the use of collaborative skills. However, due to the lack of sufficient knowledge, it was difficult for them to solve problems by understanding all the information of the problems. In the group with all low prior knowledge level students, the group tended to use collaborative skills only during the discussion. Furthermore, students with a higher level of prior knowledge tended to focus on the use of cognitive skills. However, since this type of students could solve the problems by their own knowledge and skills, in the group with all high prior knowledge level students, the group tended to use cognitive skills only, and rarely collaborated with others.

In the mixed group, which means the group is composed of high and low, or the middle-level students, the group tended to use both dimensions of CPS skills more actively and integratively.

This experiment provides some implications for researchers, teachers, and students. For instance, to researchers, it is indicated that when designing and conducting CPS-based STEM courses, it is effective to use LA approach to understand students' learning processes and to provide some evidence for effective instructional design. Considering the complex and integrative nature of CPS learning and STEM field, it is difficult for teachers to take all essential factors related to CPS and STEM into CPS-based STEM course design. Therefore, to teachers, this study indicates potential factors related to STEM learning strategy and learning behaviors, which should be paid more attention and be more encouraged during the course, in order to improve learning performance. To students, since the results indicated the indirect effects of the use of STEM learning mediated by CPS awareness, when students use STEM learning strategy during in line with CPS learning the course, especially the collaborative dimension, it shows great potential to improve learning performance finally.

Concerning the practice in CPS-based STEM education, this study provided evidence about what factors were effective and should be integrated into the instructional design. As for the perspective of research, this study indicated the effectiveness of using LA approach to understand the learning processes in practice by incorporating the integrative instructional theory and design such as CPS approach and STEM education with analytics data and insights.

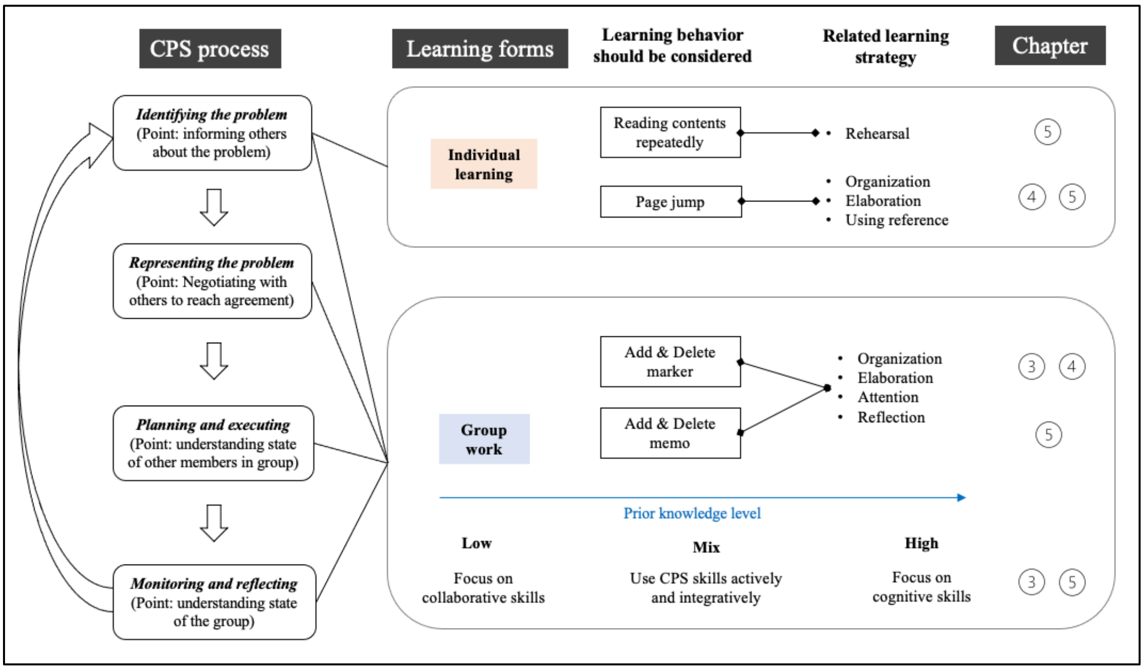


Figure 20. Important behavioral and strategic factors for CPS-based STEM design in different learning forms

6.3 Limitations and future works

In this study, the factors that improve learning performance and CPS skills were clarified, and guidance on ways to integrate these factors into the CPS-based STEM education were provided. However, there are several limitations. First, due to the limited experimental duration and teachers' experience for STEM, it was difficult for the teachers to provide comments for those unexpected solutions. As the feature of ill-defined problems, the ill-defined task is under-described and the solutions could be various. Therefore, students are likely to find unexpected solutions, requiring teachers to use their knowledge and experience to judge whether the solutions are reasonable and correct. Before the lessons, I discussed with the teachers the procedures of the lessons and the criteria for possible solutions. I asked the teachers to judge and comment on the unexpected answers according to the scientific principle and knowledge. When it is difficult for the teachers to explain the details during the class, the Moodle system can be used to provide additional references for students. For example, in Experimental Practice 5, some groups described the natural disasters in Japan during the presentations but did not know the exact mechanisms for these disasters, so the teacher provided the related reference through Moodle system after the lessons. Moreover, when the students lack the knowledge to understand the problems, the teacher can guide the students to search the related information on the Internet and provide suggestions for how to gain this knowledge. For example, in Experimental Practice 6, when solving the problem in the "Acid Rain" theme, some students did not understand the main point of the problem and focused on the wrong point. Therefore, the teacher emphasized the main point again and provided some practical suggestions about how to examine their opinion. In future work, it is necessary to provide training and guidance for the teachers about STEM teaching, such as integrating the STEM domains into the instructional designs and using technology to help them judge the unexpected answers.

Second, as the important role of engineering in STEM learning, students need to use engineering design to connect the other three STEM domains to solve problems, including applying scientific knowledge and skills, and mathematical analysis with the support of technology. However, presentations, as one of the products of CPS-based STEM learning, were assessed only by the teachers in the class. It is insufficient to judge the qualities of the outputs by the unified standard, such as the principle of creating a disaster mitigation manual and engineering thinking. In future work, it is possible to assess the output of engineering design, such as create a manual based on the engineering principles thinking.

Third, according to the results, different compositions of groups would have influence on the use of CPS skills during group work. For example, in a heterogeneous group, with different levels of prior knowledge, the use of CPS skills can be promoted. Conversely, homogeneous group with either high or low level of prior knowledge will limit the active use of CPS skills. However, in this study, all the groups were composed randomly, either according to the usual seats or the student numbers. Therefore, it is necessary to consider the group composition as one of the important factors in CPS-based STEM design and further clarify the effects of group composition, such as the individual thinking and behaviors, leadership, cognitive processes and collaborative processes in heterogeneous group or homogeneous groups.

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Appendix

Appendix A: CPS Awareness Questionnaire

1. Contents of CPS Awareness Questionnaire

Dimension	Factor	Content
Social Skills	*Participation*	Engagement with the tasks, the extent to which they attach importance to others' opinions and interact with others.
	Perspective Taking	Ability to integrate contributions from others into their own thoughts and reevaluate problems.
	Social Regulation	Strategy of recognizing the diversity of group members and negotiating with members until mutual solutions are identified.
Cognitive Skills	*Task Regulation*	Ability to analyze the problem, manage resources, set clear goals, collect information, and seek various solutions to complex situations.
	Learning and Knowledge Building	Ability to identify relationships between pieces of information, integrate knowledge from other fields or subjects, monitor outcomes, reflect on processes.

2. Items of CPS Awareness Questionnaire

Dimension	Factor	Item
Social Skills	*Participation*	Q1: I was actively participating in the science lesson. Q2: I was listening carefully when other students were speaking or making presentations. Q3: I asked others for help when I met difficulty.
	Perspective Taking	Q4: Collaborating with others is more effective in finding solutions than by oneself. Q5: It is important to receive help from others in problem solving. Q6: When facing unfamiliar problems, it is helpful to solve the problems by collaborating with others.
	Social Regulation	Q7: During the science lesson, I can recognize my advantages and disadvantages in learning. Q8: If classmates have any problems, I have the duty to help

		them. Q9: It is necessary to negotiate with other members to reach an agreement of problem solution.
Cognitive Skills	*Task Regulation*	Q10: I knew clearly about the objectives of the lesson. Q11: It is important to analyze the problems before solving them. Q12: I will investigate the information in order to solve the problems. Q13: It is not necessary to find multiple solutions for one problem.
	Learning and Knowledge Building	Q14: In science lessons, it is often necessary to use knowledge from other subjects. Q15: If I am provided enough information, I can acquire new knowledge by myself. Q16: I can organize what I have learned after the lesson. Q17: When I can't solve the problems, I will reflect on the learning.

Appendix B: Motivation Questionnaire

1. Contents of Motivation Questionnaire

Dimension	Factor	Content
Behavioral level	*Challenge*	Tendency to assume more difficult tasks than can currently be solved alone.
	Curiosity	Tendency to engage in themes and solve tasks similar to this lesson.
	Mastery	Motivation to complete goals.
Cognitive level	*Perceived Locus of Causality (Internal Causality & External Causality)*	Recognizing one's intention to perform a task is influenced by an individual/environment.
	Endogenous-Exogenous Attribution	Performing a task is treated as the goal or as a means.
Emotional level	*Enjoyment*	Enjoy learning.

2. Items of Motivation Questionnaire

Dimension	Factor	Item
Behavioral level	*Challenge*	Q1: I'd like to tackle this kind of theme. Q2: I'd like to be challenged by more difficult problems. Q3: Even when the problems are difficult, I'd like to try my best to tackle them.
	Curiosity	Q4: If time is permitted, I'd like to think about more solutions. Q5: I'm not interested in the mechanisms of natural disasters. Q6: I'd like to solve scientific problems in the real world.
	Mastery	Q7: The problems in this lesson have been successfully solved. Q8: I can remember what I have learned from the

			lesson in the future. Q9: I gave up in the lesson because the problems were too difficult to solve.
Cognitive level	*Perceived Locus of Causality*	*Internal Causality*	Q10: The aim of learning science is to know various solutions of scientific problems. Q11: Scientific knowledge is useful in daily life and learning.
		External Causality	Q12: If the teacher doesn't ask me to solve the problems, I'm not willing to do that. Q13: I'd like to solve problems by collaborating with classmates even without the teacher's help.
	Attribution	*Endogenous Attribution*	Q14: I feel so happy that I can solve the problems in the real world. Q15: I enjoy learning new knowledge of science.
		Exogenous Attribution	Q16: If it is not scored in the lesson, I'm not willing to tackle the tasks. Q17: If I can get a prize or award when I solve the problems, I will work harder.
Emotional level	*Enjoyment*		Q18: I am interested in science learning. Q19: The structure and procedure of this lesson is too complicated. Q20: Generally, I enjoyed this lesson.

Appendix C: STEM Learning Strategy Questionnaire

1. Contents of STEM Learning Strategy Questionnaire

Factor	Content
Organizing	Organizing and summarizing the important points.
Elaborating	Connecting new scientific facts with earlier ones or practical applications.
Repeating	Learning and remembering scientific facts through repetition.
Effort	Making efforts to learn science and solve problems.
Attention	Concentration on learning science and solving problems.
Time Management	Conducting individual learning or group work according to a schedule.
Learning Environment	Being willing to study somewhere that makes it easy to concentrate or find references.
Peer Learning	Collaborating with others when learning science and solving problems.
Using References	Using references for additional information.

2. Items of STEM Learning Strategy Questionnaire

Factor	Item
Organizing	Q1: I compile short summaries of the most important contents as a mnemonic aid. Q2: I go over my notes and structure the most important points. Q3: I compile a summary of the main ideas out of my notes, the script, or other sources.
Elaborating	Q4: I think of practical applications of new concepts learned from science lessons. Q5: I try to relate new knowledge or theories to knowledge or theories I already know. Q6: I think of practical examples for certain curricular facts.
Repeating	Q7: I imprint the subject matter from the lecture on my memory by repeating it. Q8: I read my notes several times in a row.

	Q9: I commit rules, technical terms, or formulas to memory.
Effort	Q10: Whenever I have planned a certain workload, I make an effort to master it. Q11: I make an effort even though the subject matter may not suit me well. Q12: I do not give up even though the problem is very difficult and complex.
Attention	Q13: When learning science, I am lacking in concentration. Q14: I am easy to distract when learning science. Q15: My concentration does not last very long.
Time Management	Q16: I work on pre-learning according to a schedule. Q17: I fix the hours I spend on pre-learning in a schedule. Q18: We work on group work according to a schedule.
Learning Environment	Q19: I want to learn science in a place that makes it easy to concentrate. Q20: I want to learn science in a place that makes it easy to find everything. Q21: When I learn science, I have the most important papers within reach.
Peer Learning	Q22: I work on tasks together with my peer students. Q23: I take time to discuss the subject matter with other students. Q24: When I am not sure about something I ask a fellow student for advice.
Using References	Q25: I search for explanatory material if certain facts are not completely clear. Q26: I look for missing information from different sources, e.g., the Internet, textbooks, or journals. Q27: When my notes are incomplete, I use additional sources.

Appendix D: Performance tests in each instructional practice

1. Post performance test for instructional practice 1

【Japanese version】

「免疫」事後確認テスト

３年７組（　　　　）番 氏名（　　　　　　　　）

１．風邪をひいたら、すぐに抗生物質を飲んだ方がよいか？
（ヒント）風邪の原因はウイルスです。抗生物質は細菌を殺す薬です。
１つまたはそれ以上選択してください：

a. 抗生物質は風邪を治すのに効果的なので、すぐに飲む方がよい
b. 抗生物質ではウイルスを殺すことはできないので、あまり飲む意味がない
c. 抗生物質は体にとって悪い菌のみを殺すので、すぐに飲む方がよい
d. 抗生物質は体によい菌も殺してしまうので、病院できちんと相談する方がよい

２．風邪薬について正しい知識はどれか？
１つまたはそれ以上選択してください：

a. 風邪薬の作用は風邪を治すものではない
b. 風邪薬はできる限り多く服用すれば効き目も高いので、症状も早く治る
c. 症状が軽いうちに風邪薬を飲むと、免疫が弱くなる可能性があり、症状が長引くことがある
d. 症状が軽いうち風邪薬を飲む方が、早く風邪を治せる

３．風邪を早く治すのに、正しい知識はどれ？
１つまたはそれ以上選択してください：

a. 抗生物質や薬を飲む
b. 体を温める
c. 良く寝る
d. 栄養が豊富な消化の良いものを食べる

【English version】

“*Immunity*” performance test

Grade 10 Class 7　Student number（　　　　）Name（　　　　　　　　）

1. If you have caught a cold, will you take the antibiotics immediately?

(Hint) The virus causes the common cold. Antibiotics are drugs that kill bacteria.

Please choose one or more answers:

a. We should take the antibiotics immediately since antibiotics are effective in curing common colds.
b. We don’t need to take antibiotics since antibiotics can't kill the virus.
c. We should take antibiotics immediately since antibiotics kill the bad bacteria for the body only.
d. It's better to consult doctors since antibiotics also kill good bacteria.

2. Which is (are) correct about cold remedies?

Please choose one or more answers:

a. The cold remedies cannot cure a common cold.
b. If we take as many cold remedies as possible, the body will be healed quickly.
c. Taking cold remedies while the symptoms are mild may weaken the immune system and prolong the symptoms.
d. Taking cold remedies while the symptoms are mild can cure a cold faster.

3. Which is (are) the correct measure(s) to cure a cold?

Please choose one or more answers:

a. Taking antibiotics or cold remedies
b. Warming the body
c. Sleeping well
d. Eating nutritious and digestible foods

2. Pre-post performance test for instructional practice 2

【Japanese version】

「湖水爆発」事前（事後）確認テスト

３年７組（　　　　）番 氏名（　　　　　　　　）

１．二酸化炭素の実験室での作り方は、以下のどれですか？

a. 貝殻（炭酸カルシウム）に塩酸を加える

b. 二酸化マンガンに過酸化水素水（オキシドール）を加える

c. 鉄に塩酸を加える

d. 塩化アンモニウムに水酸化カルシウムを加える

２．二酸化炭素の工業的製法に関係する事項はどれですか？

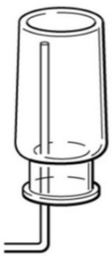
a. ケイ砂（主成分は二酸化ケイ素）を融解して固化させる

b. ボーキサイトから、電気分解して取り出す

c. 化石燃料を燃やした後で、発生した気体を圧縮して液化させる

d. 鉄鉱石、コークス、石灰石を溶鉱炉に入れると、液状の物質が生成される

３．二酸化炭素の気体の集め方は、次の３つのうちどれですか？



a. 上方置換法

b. 水上置換法

c. 下方置換法

４．問３で選んだ理由として考えられる二酸化炭素の特徴を２つ述べよ。

５．炭酸は二酸化炭素が水に溶けたものである。周囲の圧力が大きいと次の化学反応式は、右と左どちらに反応が進むと考えられますか？

（ヒント：圧力が高くなると、圧力を下げるように反応が進みます。）

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$

６.問５において､周囲の圧力が低いと､左と右どちらに反応が進むと考えられますか？

【English version】

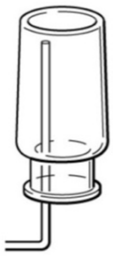
“*Limnic Eruption*” performance test

Grade 10 Class 7　Student number（　　　　）Name（　　　　　　　　）

1. Which of the laboratory preparation of carbon dioxide?
   a. Add hydrochloric acid to shells (calcium carbonate)
   b. Add hydrogen peroxide solution to manganese dioxide
   c. Add hydrochloric acid to iron
   d. Add calcium hydroxide to ammonium chloride

2. Which of the following is related to the industrial production of carbon dioxide?
   a. Melt and solidify silica sand (the main component is silicon dioxide)
   b. Electrolyze and remove from bauxite
   c. Burn fossil fuels, then compress and liquefy the generated gas
   d. Put iron ore, coke (carbon), and limestone into a blast furnace, produce liquid substances

3. Which of the following is (are) the correct collection method(s) of carbon dioxide?



a. Upward delivery

b. Water displacement

c. Downward delivery

4. As the reasons for your choice in Question 3, please describe two possible characteristics of carbon dioxide.

5. Carbonic acid is carbon dioxide dissolved in water. In the following chemical reaction formula, when the ambient pressure is high, do you think the reaction will proceed to the left or right? (Hint: When the pressure increases, the reaction proceeds to decrease the pressure.)

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$

6. In Question 5, if the ambient pressure is low, do you think the reaction will proceed to the left or right?

3. Pre-post performance test for instructional practice 3

【Japanese version】

「免疫」事前（事後）確認テスト

３年７組（　　　　）番 氏名（　　　　　　　　）

１．以下の病気は遺伝病に属するのは

a. 風邪

b. 公害病の水俣病

c. 糖尿病

d. ヨウ素の過剰摂取による甲状腺炎

２．１つの遺伝子のわずかな違いにより起こる病気は________遺伝子病という。

３. 複数の遺伝子と環境要因の相互作用により発症する病気は________遺伝子病という。

４．以下の問題は正しいか（○)、間違いか（✖）

（１）全ての遺伝子病は先天性疾患である。　（　　）

（２）全ての先天性疾患は遺伝子病である。　（　　）

（３）病気の原因となる遺伝子を持っている人は、必ず発病する。　（　　）

５．遺伝病について、誤っているのはどれか。

a. 遺伝子の突然変異は、遺伝病を起こすことになる

b. 染色体の構造の異常は、遺伝病を起こすことになる

c. 多くの病気は、遺伝子と環境両方の影響を受ける

d. 優性遺伝病の遺伝因子を持っている人は、産んだ赤ちゃんが必ず発病する

６．病気の原因となる環境の要因は何があるか。３つの例をあげてください。

【English version】

“*Immunity*” performance test

Grade 10 Class 7　Student number（　　　　）Name（　　　　　　　　）

1. Which of the following belong(s) to genetic disease(s)?
   a. Cold
   b. Minamata disease (a pollution disease)
   c. Diabetes
   d. Thyroiditis due to overdose of iodine

2. Diseases caused due to slight differences in one gene are called ________ genetic diseases.

3. Diseases caused due to the interaction of multiple genes and environmental factors are called ________ genetic diseases.

4. Are the following descriptions True (○) or False (✕)?
   (1) All genetic diseases are congenital diseases. (　)
   (2) All congenital diseases are genetic diseases. (　)
   (3) People who have genes that cause illness will definitely get sick. (　)

5. Which of the following is (are) wrong about genetic diseases?
   a. Gene mutations will cause genetic diseases
   b. Abnormalities in the structure of chromosomes will cause genetic diseases
   c. Many diseases are affected by both genetics and the environment
   d. The baby of the people who have the genetic factors of dominant genetic disease will get sick

6. What are the environmental factors that cause illness? Please describe three examples.

4. Pre-post performance test for instructional practice 4

【Japanese version】

「湖水爆発」事前（事後）確認テスト

1年　　組　　番　　グループ番号＿＿＿＿＿＿　　氏名＿＿＿＿＿＿

１．以下の問題が正しいければ（○)、誤っていれば（✖)、分からなければ（？）と回答しなさい。

（1）二酸化炭素は無色・無臭である　（　　）

（2）二酸化炭素は水に溶ける　（　　）

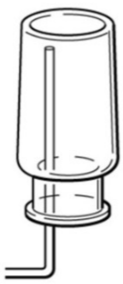
（3）二酸化炭素気体は酸性である　（　　）

（4）二酸化炭素の水溶液は酸性である　（　　）

（5）二酸化炭素はアルカリ性の水溶液に吸収されやすい（　　）

（6）温室効果ガスは二酸化炭素しかない　（　　）

２．二酸化炭素の気体の集め方として適切なのは次のうちどれですか。



a. 上方置換法

b. 水上置換法

c. 下方置換法

３．問２の答えを選んだ理由はなんですか。次の中から１つまたは複数選択してください。

a. 空気より軽い　　b. 水に溶けない

c. 水に溶ける　　d. 空気より重い

４．気体の溶解度は、一般に気体の圧力が 1.0×10^{5}Pa のとき、一定量の溶媒に溶解する気体の物質量や質量、体積で表すことが多い。

気体の溶解度は温度が上がると、どうなるか。

a. 大きくなる　　b. 小さくなる

５．気体の溶解度は、一般に気体の圧力が 1.0×10^{5}Pa のとき、一定量の溶媒に溶解する

気体の物質量や質量、体積で表すことが多い。
気体の溶解度は、圧力が上がると、どうなるか。

a. 大きくなる　　　　b. 小さくなる

６．炭酸水とは、二酸化炭素（炭酸ガス）を含む水のことをいいます。炭酸水を調べてみると、血行促進や美容などの意外な効果がある。
炭酸ガスを水に溶かし込むためには、次のどの操作をすれば良いか。
一つ選択してください。

a. 減圧、昇温　　　b. 加圧、昇温
c. 減圧、降温　　　d. 加圧、降温

７．真夏の太陽の下、締め切った車の中は異常なほど高温になります。気温３５℃のとき、車内の最高気温は５７℃、運転席前のダッシュボード上の気温は７９℃に達したというデータがあります。車内に香水のビンや液体が入った容器などを放置しておくと破裂する可能性がありますが、その理由を説明してください。

８．地球上に広がるこの世界は、美しく素晴らしい場所であると同時に恐ろしい場所でもあります。
日本は、台風、豪雨、地震、津波、火山、大雪、日本は自然災害が多い国です。私たちは、できるだけ自然災害による被害を減らしながら、自然と共に生きていかなければなりません。災害の経験は、再び悲劇が起こることを防ぐための教訓として活かされます。
災害を受けて、国は法律の整備や船舶への適切な数の救命ボート整備、火災の際の非常口、救急隊の確保など、多くの対策を取ってきました。
自然災害による被害を減らすために、わたしたち個人の立場としては、何を行ったらよいと思いますか。

【English version】

“*Limnic Eruption*” **performance test**

Grade 7 Class__ Student number________ Group number________

Name____________

1. Please answer whether the following questions are True(○), False (✕), or you do not know (?).

(1) Carbon dioxide is colorless and odorless. ( )

(2) Carbon dioxide dissolves in water. ( )

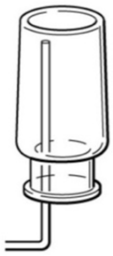
(3) Carbon dioxide gas is acidic. ( )

(4) The aqueous solution of carbon dioxide is acidic. ( )

(5) Carbon dioxide is easily absorbed by an alkaline aqueous solution. ( )

(6) Carbon dioxide is the only greenhouse gas. ( )

2. Which of the following is (are) the correct collection method(s) of carbon dioxide?



a. Upward delivery

b. Water displacement

c. Downward delivery

3. What’ the reason(s) for your choice in Question 2? Please select one or more correct answers from the following.

a. Lighter than air b. Insoluble in water

c. Soluble in water d. Heavier than air

4. The solubility of the gas is generally expressed by the amount of substance, mass, or volume of the gas dissolved in a certain amount of solvent when the pressure of the gas is 1.0 × 105 Pa. How will the solubility of a gas change as the temperature rises?

a. It increases b. It decreases

5. The solubility of the gas is generally expressed by the amount of substance, mass, or volume of the gas dissolved in a certain amount of solvent when the pressure of the gas is 1.0 × 105 Pa.

How will the solubility of a gas change as the pressure rises?

a. It increases		b. It decreases

6. Carbonated water is the water that contains carbon dioxide. Carbonated water has unexpected effects such as promoting blood circulation and beauty.

Which of the following operations is correct to dissolve carbon dioxide in water?

a. Decompressing and increasing temperature
b. Pressurizing and increasing temperature
c. Decompressing and decreasing temperature
d. Pressurizing and decreasing temperature

7. Under the midsummer sun, the temperature inside a closed car becomes abnormally high. When the temperature is 35 °C, the maximum temperature inside the car possibly reaches 57 °C, and the temperature on the dashboard in front of the driver's seat possibly reaches 79 °C. If you leave a bottle of perfume or a container containing liquid in the car, it may explode. Please explain the reason.

8. The earth contains a beautiful and wonderful world, however, as well as some terrifying places. Japan has many natural disasters such as typhoons, heavy rains, earthquakes, tsunamis, volcanoes, and heavy snow. We must live with nature while reducing the damage caused by natural disasters as much as possible. We can use what we learned from a disaster as the experience to prevent the same tragedy. When facing disasters, the country has taken many measures, including legislation, the provision of an appropriate number of lifeboats on ships, emergency exits in the event of a fire, and the securing of ambulance crews.

What do you think we should do from an individual standpoint to reduce the damage caused by natural disasters?

5. Pre-post performance test for instructional practice 5

【Japanese version】

「湖水爆発」事前（事後）確認テスト

１年　　組　　番　　　氏名__________

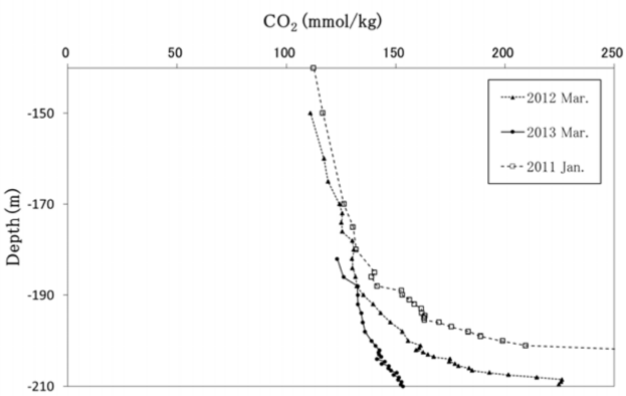
１．以下の問題が正しければ（○）、誤っていれば（✖）、分からなければ（？）と回答しなさい。

（1）二酸化炭素は無色・無臭である。　　　　（　　）

（2）二酸化炭素の水溶液は酸性である。　　　（　　）

２．この図は 2011～2013 年にある湖に溶ける CO_2 の量と湖水の深度との関係です。この図によると、この湖に溶存する CO_2 は、湖面と湖底のどちらに溜まっていると考えられますか？

a. 湖面　　　　　b. 湖底



３．CO_2 は湖面/湖底に溜まっていると考えられる理由は何ですか？

４．気体の溶解度は、一般に気体の圧力が 1.0×10^5Pa のとき、一定量の溶媒に溶解する気体の物質量や質量、体積で表すことが多い。

気体の溶解度は温度が上がると、どうなるか。

a. 大きくなる　　　　b. 小さくなる

５．気体の溶解度は、一般に気体の圧力が 1.0×10^5Pa のとき、一定量の溶媒に溶解する気体の物質量や質量、体積で表すことが多い。

気体の溶解度は、圧力が上がると、どうなるか。

a. 大きくなる　　　　b. 小さくなる

６．炭酸水とは、二酸化炭素（炭酸ガス）を含む水のことをいいます。炭酸水を調べてみると、血行促進や美容などの意外な効果がある。
炭酸ガスを水に溶かし込むためには、次のどの操作をすれば良いか。
一つ選択してください。

a. 減圧、昇温　　b. 加圧、昇温
c. 減圧、降温　　d. 加圧、降温

７．真夏の太陽の下、締め切った車の中は異常なほど高温になります。気温３５℃のとき、車内の最高気温は５７℃、運転席前のダッシュボード上の気温は７９℃に達したというデータがあります。車内に香水のビンや液体が入った容器などを放置しておくと破裂する可能性がありますが、その理由を説明してください。

８．以下表には 1.01×10^5 Pa の時、１L 水への二酸化炭素の溶解度を示しています。

温度（℃）	0	20	40	60	80
溶解度(mol)	0.0765	0.0390	0.0237	0.0166	0.0130

20℃で、2.02×10^5 Pa の二酸化炭素が水 1.0L に接しています、この時、水 1.0L に溶けている二酸化炭素の質量はいくらですか。

a. 1.72g　　b. 3.43g
c. 0.039g　　d. 0.078g

９．二酸化炭素で人間と動物が窒息になる原因は？

１０．地球上に広がるこの世界は、美しく素晴らしい場所であると同時に恐ろしい場所でもあります。
日本は、台風、豪雨、地震、津波、火山、大雪、日本は自然災害が多い国です。私たちは、できるだけ自然災害による被害を減らしながら、自然と共に生きていかなければなりません。災害の経験は、再び悲劇が起こることを防ぐための教訓として活かされます。災害を受けて、国は法律の整備や船舶への適切な数の救命ボート整備、火災の際の非常口、救急隊の確保など、多くの対策を取ってきました。
自然災害による被害を減らすために、わたしたち個人の立場としては、何を行ったらよいと思いますか。

【**English version**】

"*Limnic Eruption*" performance test

Grade 10 Class__ Student number________ Name____________

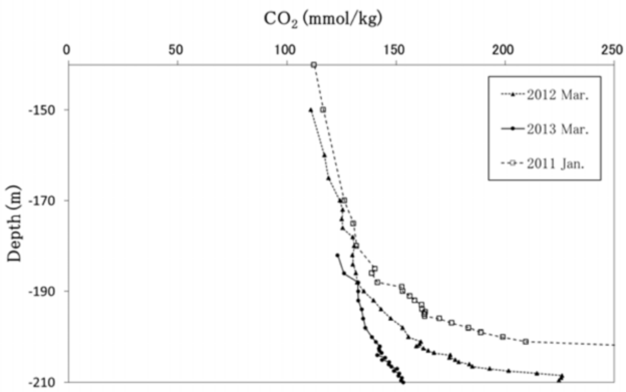
1. Please answer whether the following questions are True (○), False (✕), or you do not know (?).

(1) Carbon dioxide is colorless and odorless. ( )

(2) The aqueous solution of carbon dioxide is acidic. ( )

2. This figure shows the relationship between the amount of CO_2 dissolved in the lake and the depth of the lake in 2011-2013. According to this figure, do you think that the CO_2 dissolved in this lake accumulates on the surface or the bottom of the lake?

a. On the surface of the lake b. On the bottom of the lake



3. Why do you think CO_2 is accumulated on the surface/bottom of the lake?

4. The solubility of the gas is generally expressed by the amount of substance, mass, or volume of the gas dissolved in a certain amount of solvent when the pressure of the gas is 1.0 × 105 Pa. How will the solubility of a gas change as the temperature rises?

a. It increases b. It decreases

5. The solubility of the gas is generally expressed by the amount of substance, mass, or volume of the gas dissolved in a certain amount of solvent when the pressure of the gas is 1.0 × 105 Pa. How will the solubility of a gas change as the pressure rises?

a. It increases b. It decreases

6. Carbonated water is water that contains carbon dioxide. Carbonated water has unexpected effects such as promoting blood circulation and beauty.
Which of the following operations is correct to dissolve carbon dioxide in water?

a. Decompressing and increasing temperature
b. Pressurizing and increasing temperature
c. Decompressing and decreasing temperature
d. Pressurizing and decreasing temperature

7. Under the midsummer sun, the temperature inside a closed car becomes abnormally high. When the temperature is 35 °C, the maximum temperature inside the car possibly reaches 57 °C, and the temperature on the dashboard in front of the driver's seat possibly reaches 79 °C. If you leave a bottle of perfume or a container containing liquid in the car, it may explode. Please explain the reason.

8. This table shows the solubility of carbon dioxide in 1 L of water at 1.01 x 105 Pa.

Temperature (°C)	0	20	40	60	80
Solubility (mol)	0.0765	0.0390	0.0237	0.0166	0.0130

At 20 °C, 2.02×10^5 Pa, what is the mass of carbon dioxide dissolved in 1.0 L of water?

a. 1.72g　　b. 3.43g
c. 0.039g　　d. 0.078g

9. What's the reason that carbon dioxide causes humans and animals' suffocation?

10. The earth contains a beautiful and wonderful world, however, as well as some terrifying places. Japan has many natural disasters such as typhoons, heavy rains, earthquakes, tsunamis, volcanoes, and heavy snow. We must live with nature while reducing the damage caused by natural disasters as much as possible. We can use what we learned from a disaster as the experience to prevent the same tragedy. When facing disasters, the country has taken many measures, including legislation, the provision of an appropriate number of lifeboats on ships, emergency exits in the event of a fire, and the securing of ambulance crews.
What do you think we should do from an individual standpoint to reduce the damage caused by natural disasters?

6. Pre-post performance test for instructional practice 5

(a) *The Formation of Solutions* (the data were not collected)

【Chinese version】

8.1 课前（课后）测验

一、填空

1. 蔗糖可以溶解在水中，形成蔗糖________，其中水是__________，蔗糖是__________。

2. 水是许多物质的溶剂。我们通常可以依据物质能不能溶于水，而将其分为____________________和____________________。

3. 汽油是油漆的_____________，因此它可以用来去除油漆。

二、配对

4. 找出左右栏中相关的项目，用短线连接起来。

蒸馏法	一种溶液
酒 精	一种提炼纯水的方法
蔗糖溶液	一种水以外的溶剂

三、选择

5. 可以加快溶质溶解的一般因素有（　　）。

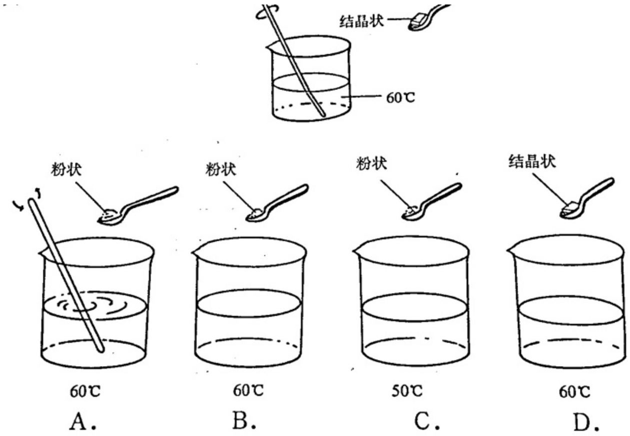
① 溶质呈粉状　② 溶剂的温度高　③ 溶解过程中加以搅拌

A. 只有①　B. ①和②　C. ①和③　D. 全部都是

6. 假如你的尼龙衣物沾上油漆，你会用以下哪种性质的溶剂来清洗衣服呢？（　　）

溶剂	对油漆	对尼龙
A.	能溶解	能溶解
B.	能溶解	不能溶解
C.	不能溶解	能溶解
D.	不能溶解	不能溶解

7. 小明想知道搅拌能不能影响溶质溶解的快慢。她应该进行下列图中的哪个实验作为对照？（　　）



四、问题

8. 试解释“干洗”的原理。

____

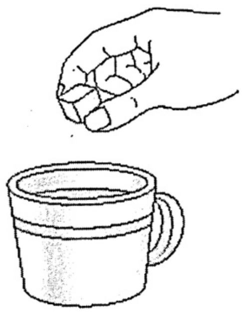
____

9. 写出三种加快糖块在奶茶中溶解的方法。

____

____

____



【English version】

8.1 Performance test

I. Fill-in-the-Blank Questions

1. Sucrose can be dissolved in water to form sucrose ________, where water is __________ and sucrose is __________.

2. Water is a solvent for many substances. We can usually divide substances into ___________ and __________ based on whether they can be dissolved in water.

3. Gasoline is the _____________ of paint, so it can be used to remove paint.

II. Matching Questions

4. Find the related items in the left and right columns and connect them with short lines.

Distillation	One kind of solution
Alcohol	A method for refining pure water
Sucrose solution	A solvent other than water

III. Multiple-choice questions

5. The general factors that can accelerate the dissolution of solutes are (   ).

① the solute is powdery

② the temperature of the solvent is high

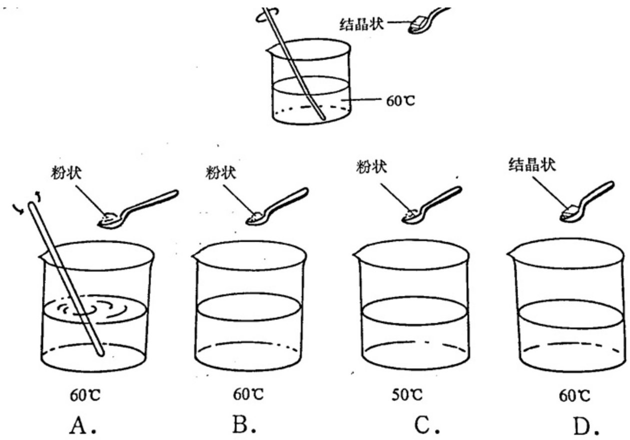
③ stirring during the dissolution process

A. Only ①   B. ① and ②   C. ① and ③   D. All

6. If your nylon clothes are stained with paint, which of the following solvents would you use to clean the clothes? (   )

Solvent	To paint	To nylon
A.	Soluble	Insoluble
B.	Soluble	Insoluble
C.	Insoluble	Insoluble
D.	Insoluble	Insoluble

7. Ming wanted to know if stirring could affect the speed of solute dissolution. Which of the following should she perform as a control experiment? (   )



IV. Descriptive questions

8. Please explain the principle of “dry cleaning”.

____

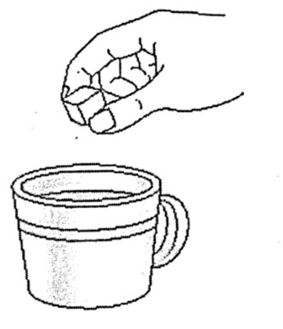
____

9. Describe three ways to speed up the dissolution of sugar cubes in milk tea.

____

____

____



(b) *Various Types of Solutions*

【Chinese version】

8.2 课前（课后）测验

一、填空

1. 有些物质中的色素遇酸性溶液和碱性溶液会分别显现不同的颜色，我们把这些物质称为_____________。

2. 紫色石蕊试液遇酸性溶液变_______色，遇碱性溶液变_______色，无色酚酞试液遇酸性溶液_______色，遇碱性溶液变_______色。

3. 溶液的酸碱性强弱可用_______来表示，其范围通常在_____至_____之间。
pH=2 的溶液显_____性；pH=8 的溶液显_____性。

4. 食品和日用品中，呈酸性的有_______，_______；呈碱性的有_______，_______。

5. 用 pH 试纸测定溶液的 pH 时，应用________蘸取溶液沾到试纸上，而不应把试纸浸入溶液，以免________溶液。

二、选择

6. 在实验室中用于测定溶液酸碱性强弱的 pH 试纸（适用范围在 1~14）常见的颜色为（　　）。
   A. 黄色　　B. 白色　　C. 蓝色　　D. 红色

7. 下列液体中呈碱性的是（　　）。
   A. 可乐　　B. 漂白水　　C. 柠檬汁　　D. 鲜奶

8. 在下列各组物质中，能用酚酞试液区分的是（　　）。
   A. 盐酸和蒸馏水　　B. 氢氧化钠溶液和硫酸
   C. 石灰水和氢氧化钠溶液　　D. 蒸馏水和食盐水

9. 某些食物的近似 pH 为：牛奶 6.3~6.；葡萄 3.5~4.5；玉米粥 6.8~8.0；苹果 2.9~3.3。其中酸性最强的是（　　）。
   A. 葡萄　　B. 牛奶　　C. 玉米粥　　D. 苹果

10. 人体内的一些液体的pH如下：胰液7.~8.0；胆汁6.8~7.4；胃液0.8~1.5；血浆7.35~7.45。其中只显酸性的液体是（　　　）。

A. 胆汁　　　　B. 血浆　　　　C. 胃液　　　　D. 胰液

11. 有甲、乙、丙、丁四瓶溶液，它们的pH次是2.8、4.5、7.0、10.2，则（　　　）。

A. 甲溶液能使紫色石蕊试液变红色

B. 乙溶液能使无色酚酞溶液变红色

C. 丙溶液能使紫色石蕊试液变无色

D. 丙溶液与丁溶液混合后，混合液体呈中性

三、问题

12. 下表是几种常见物质的pH。

物质	pH
洗衣粉溶液	11
西柚汁	3
浓玻璃清洁剂	13
氨水	9

把表中各物质分成酸性物质和碱性物质两类。

酸性物质：____________________

碱性物质：____________________

哪一种物质的碱性最强？________________

哪一种物质的酸性最强？________________

13. 如何确定某无色溶液是不是碱性溶液？简述你所知道的实验方法。（至少列举三种方法）

____

____

____

【English version】

8.2 Performance test

I. Fill-in-the-Blank Questions

1. The pigments in some substances will show different colors when encountering acidic solutions and alkaline solutions. These substances are called _____________.

2. Litmus turns _____ (color) in acidic solutions, turns _____ (color) in alkaline solutions; Phenolphthalein turns _____ (color) in acidic solutions, turns _____ (color) in alkaline solutions.

3. The acidity and alkalinity of the solution can be measured by _______, and its range goes from _____ to _____.
The solution with pH=2 is _____ (acidic, neutral or alkaline); the solution with pH=8 is _____ (acidic, neutral or alkaline).

4. Regarding foods and daily necessities, ________ and ________ are acidic; ________ and ________ are alkaline.

5. When using pH test paper to measure the pH of a solution, we should use ______ to dip the solution onto the test paper, instead of immersing the test paper in the solution to avoid _______ solution.

II. Multiple-choice questions

6. The color of the pH test paper used in the laboratory to determine the level of acidity or alkalinity of a solution (on a scale from 0-14) is (　　　).
   A. yellow　　B. white　　C. blue　　D. red

7. In the following, the alkaline liquid is (　　　).
   A. coke　　B. bleach　　C. lemon juice　　D. milk

8. Among the following pair of substances, what can be distinguished by phenolphthalein is (　　).
   A. hydrochloric acid and distilled water
   B. sodium hydroxide solution and sulfuric acid
   C. limewater and sodium hydroxide solution

D. distilled water and saline solution

9. The approximate pH of some foods are: milk 6.3-6; grape 3.5-4.5; polenta 6.8-8.0; apple 2.9-3.3. Among them, the most acidic food is (   ).

A. grape　　B. milk　　C. polenta　　D. apple

10. The pH of some fluids in the human body is as follows: pancreatic juice 7.0~8.0; bile 6.8~7.4; gastric juice 0.8~1.5; plasma 7.35~7.45. The only acidic liquid is (   ).

A. Pancreatic juice　　B. Bile　　C. Gastric juice　　D. Plasma

11. There are four bottles of solutions of A, B, C, and D. Their pH levels are 2.8, 4.5, 7.0, 10.2, then (   ).

A. purple litmus turns red in A solution

B. colorless phenolphthalein turns red in B solution

C. purple litmus turns colorless in C solution

D. after mixing C solution and D solution, the mixed liquid is neutral

III. Descriptive questions

12. The following table shows the pH of several common substances.

Substance	pH
Washing powder solution	11
Grapefruit juice	3
Concentrated glass cleaner	13
Ammonia	9

The substances in the table are divided into two types: acidic substances and alkaline substances.

Acidic substance: ______________________________

Alkaline substance: ______________________________

Which substance is the most alkaline? ______________________

Which substance is the most acidic? ______________________

13. How to determine whether a colorless solution is an alkaline solution? Briefly describe at least three experimental methods.

____

____

____

(c) *Using Solutions Safely*

【Chinese version】

8.3 课前（课后）测验

一、填空

1. 土壤的酸碱性强弱公响植物的生长。下表列出了一些植物适合生长的土壤 pH 范围。

植物	茶	油菜	西瓜	甜菜
最适宜的 pH 范围	4.5~5.5	5.8-6.7	6.0~7.0	7.0~7.5

某地区土壤显弱酸性。请参照上表，从土壤的酸碱性考虑，在这一地区不适宜种植的植物是__________。为了改良这一地区的土壤，农民通常在土壤里施加__________，使其适合种植这种植物。

2. 酸雨是指 pH________的大气降水。引起酸雨的主要物质是__________和__________。

3. 酸溶液和碱溶液混合时，会使对方的酸性和碱性减弱，这种过程称为中和作用。当酸溶液和碱溶液正好中和时，混合溶液的 pH 应为________。

二、选择

4. 胃酸过多会引起胃部不适，为了缓解不适，可以服用（　　　）。

A. 啤酒　　B. 柠檬水　　C. 胃舒宁　　D. 可乐

5. 以下是上海市空气质量指标监测的几个项目，其中可用于预测上海的酸雨污染情况的是（　　　）。

① 二氧化硫　② 二氧化氮　③ 可吸入颗粒物

A. ①和②　　B. ②和③　　C. ①和③　　D. ①、②和③

6. 酸雨给我们带来的危害有（　　　）。

① 影响植物的光合作用　② 腐蚀建筑物和金属制品

③ 使江湖水质酸化，水生物死亡　④ 影响人体健康

A. ①和②　　B. ①、②和③

C. ①、②、③和④　　D. ①和④

三、问题

7. 正常雨水的 pH 通常小于 7，但不等于 7，这是为什么？

提示：可以先测定二氧化碳气体通入蒸馏水后形成溶液的 pH。

____

8. 小王同学做“酸雨”对幼苗成长影响的实验。他在标有 A、B、C 的三个相同的烧杯内铺上棉花，每个烧杯里放 20 棵小幼苗，并用棉花包住根部，再向三个烧杯内加入适量的不同液体（模仿酸雨），然后将三个烧杯放在实验室靠窗的地方。过几天观察这些幼苗，实验记录见下表。

烧杯	A	B	C
液体	蒸馏水	稀硫酸	稀硝酸
pH	7	1	2
几天后	长得很高	死亡	死亡

（1）本实验的对照组是____________。

（2）本实验中假设影响植物生长的变量是____。

（3）做实验时，应保持相同的条件是光照、____________和______________________。

（4）从表中记录结果看，此实验表明____。

【English version】

8.3 Performance test

I. Fill-in-the-Blank Questions

1. The level of acidity and alkalinity of the soil affects the growth of plants. The following table lists some suitable soil pH ranges for plant growth.

Plant	Tea	Brassica rapa	Watermelon	Sugar beet
suitable pH range	4.5~5.5	5.8-6.7	6.0~7.0	7.0~7.5

The soil in a certain area is weakly acidic. Please refer to the above table. Considering the pH of the soil, the plants that are not suitable for planting in this area are __________. In order to improve the soil in this area, farmers usually apply __________ to the soil to make it suitable for planting this plant.

2. Acid rain refers to atmospheric precipitation with pH________. The main substances that cause acid rain are __________ and __________.

3. When the acid solution and alkali solution are mixed, the acidity and alkalinity of each other will be weakened. This process is called neutralization. When the acid solution and the alkali solution are neutralized, the pH of the mixed solution should be ________.

II. Multiple-choice questions

4. Too much stomach acid will cause stomach discomfort. In order to relieve the discomfort, you can take (   ).

A. beer   B. lemonade   C. stomach medicine   D. Coke

5. The following are several items monitored by Shanghai's air quality indicators. Among them, which can be used to predict the acid rain pollution in Shanghai is (   ).

① sulfur dioxide   ② nitrogen dioxide   ③ inhalable particulate matter

A. ① and ②   B. ② and ③   C. ① and ③   D. ①, ② and ③

6. The harmful effects caused by acid rain are (   ).

① affecting the photosynthesis of plants

② corroding the buildings and metal products

③ acidifying rivers and lakes and killing aquatic organisms

④ affecting human health

A. ① and ②　　B. ①, ② and ③

C. ①, ②, ③ and ④　　D. ① and ④

III. Descriptive questions

7. The pH of normal rainwater is usually less than 7, but not equal to 7, why is this?

Hint: You can first measure the pH of the solution that dissolving carbon dioxide gas in distilled water.

____

8. Wang conducted an experiment on the influence of "acid rain" on the growth of seedlings. He spread cotton in three identical beakers marked A, B, and C, put 20 small seedlings in each beaker, covered the roots with cotton, and then added appropriate amounts of different liquids to the three beakers (simulating acid rain), and then placed the three beakers near the window of the laboratory. He observed these seedlings in a few days and recorded the experimental results in the table below.

Beaker	A	B	C
Liquid	distilled water	dilute sulfuric acid	dilute nitric acid
pH	7	1	2
A few days later	grow well	die	die

(1) The control group of this experiment is ____________.

(2) In this experiment, it is assumed that the variable that affects plant growth is (are) ________________________________.

(3) When doing experiments, the same conditions should be maintained including light, __________ and ________________.

(4) From the results recorded in the table, this experiment shows that ______________________.

(d) *Limnic Eruption*

【Chinese version】

湖水爆炸 课前（课后）测验

一、判断

下列关于二氧化碳的说法，请判断正误。

1. 二氧化碳可溶于水。 (　　)
2. 二氧化碳溶于水后溶液是酸性的。 (　　)
3. 二氧化碳溶于水后溶液是碱性的。 (　　)
4. 二氧化碳是有毒物质。 (　　)

二、填空

5. 二氧化碳溶于水后形成碳酸________，水是________（填溶质/溶剂/溶液）。

三、选择

6. 下列说法中正确的是（多选题）

A. 二氧化碳量少时也会对人体有害。

B. 二氧化碳超过一定量时才会对人体有害。

C. 为了减少二氧化碳浓度，应该经常保持室内通风。

D. 二氧化碳浓度过高对人体有害，所以我们应该杜绝二氧化碳的排放。

E. 摇晃碳酸饮料瓶子时，大量二氧化碳气体从液体中释放出，会引起液体喷发甚至瓶子爆炸。

【English version】

“*Limnic Eruption*” Performance test

I. True or False

Are the following descriptions True or False?

(1) Carbon dioxide is soluble in water. ( )

(2) When carbon dioxide is dissolved in water, the solution is acidic. ( )

(3) When carbon dioxide is dissolved in water, the solution is alkaline. ( )

(4) Carbon dioxide is a toxic substance. ( )

II. Fill-in-the-Blank Questions

5. When carbon dioxide is dissolved in water, the carbonic acid ________ is formed, in this, the water is ________ (solute, solvent, or solution).

III. Multiple-choice questions

6. Which of the following statements is correct?

Choose one or more answers.

A. Carbon dioxide is also harmful to the human body even the amount of carbon dioxide is small.

B. Carbon dioxide is only harmful to humans when it exceeds a certain amount.

C. In order to reduce the concentration of carbon dioxide, it is necessary to maintain the indoor ventilation frequently.

D. Excessive carbon dioxide concentration is harmful to the human body, so we should stop carbon dioxide emissions.

E. When shaking a bottle of carbonated drink, a large amount of carbon dioxide gas will be released from the liquid, which can cause the liquid to erupt or even explode the bottle.

Publications related to this dissertation

Articles (Refereed)

1. Chen, L., Inoue, K., Goda, Y., Okubo, F., Taniguchi, Y., Oi, M., ... & Yamada, M. (2020). Exploring Factors that Influence Collaborative Problem Solving Awareness in Science Education. Technology, Knowledge and Learning, 25, 337–366. (Chapter 3)
2. Chen, L., Yoshimatsu, N., Goda, Y., Okubo, F., Taniguchi, Y., Oi, M., ... & Yamada, M. (2019). Direction of collaborative problem solving-based STEM learning by learning analytics approach. Research and Practice in Technology Enhanced Learning, 14(1), 1–28. (Chapter 4)

Proceedings of international conferences (Refereed)

1. Chen, L., Taniguchi, Y., Shimada, A., and Yamada, M. (2020) How to Design Collaborative Problem Solving-based STEM Lessons based on the Perspective of Learning Behaviors? Proceedings of IEEE TALE 2020, 410-417. (Chapter 5)
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3. Chen, L., Uemura, H., Goda, Y., Okubo, F., Taniguchi, Y., Oi, M., Konomi, S., Ogata, H., & Yamada, M. (2018). Instructional Design and Evaluation of Science Education to Improve Collaborative Problem Solving Skills. Proceedings of Society for Information Technology & Teacher Education International Conference (pp. 1306-1311). Washington, D.C., United States: Association for the Advancement of Computing in Education (AACE) (Chapter 3)

Other publications： Proceedings of international conferences (Refereed)

1. Chen, L., Lu, M., Goda, Y., Shimada, A., and Yamada, M. (2020). Factors of the use of learning analytics dashboard that affect metacognition, Proceedings of CELDA 2020, pp.295-302. (Best Paper Award)
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4. Chen, L., Goda, Y., Shimada, A., Yamada, M. (2019). Factors investigation of learning behaviors affecting learning performance and self-regulated learning, Proceedings of IEEE TALE 2019, 676-681.
5. Chen, L., Lu, M., Goda, Y., & Yamada, M. (2019). Design of learning analytics dashboard supporting metacognition. Proceedings of 16th International Conference Cognition and Exploratory Learning in Digital Age (CELDA 2019), 175-182.