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Learning with collaborative inquiry: a science learning environment for secondary students

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When inquiry-based learning is designed for a collaborative context, the interactions that arise in the learning environment can become fairly complex. While the learning effectiveness of such learning environments has been reported in the literature, there have been fewer studies on the students' learning processes. To address this, the article presents a study of science learning in a computer-supported learning environment called Collaborative Science Inquiry (CSI), which integrates guided inquiry principles for activity design, employs modelling and visualisation tools for promoting conceptual understanding and incorporates key computer-supported collaborative learning (CSCL) elements for enabling students' collaboration. With the aim of understanding the process of students' conceptual changes supported by the CSI learning environment as used in a secondary school, data on students' test achievements, responses to learning tasks and peer discussions in collaboration were collected, analysed and discussed. The results of the qualitative and quantitative data analysis indicated that guided inquiry coupled with CSCL elements facilitated by the CSI system can engage students in inquiry activities and promote their conceptual understanding in a progressive way.

Keywords: CSI system; science learning; collaborative inquiry; conceptual understanding

1. Introduction

Existing literature has well documented the benefits of collaborative pedagogies. Researchers have devoted substantial efforts to designing and evaluating computer-supported collaborative learning (CSCL) applications in classrooms. Among these applications, a good number of CSCL elements are deployed, including shared (work) spaces, discussion forums, chat tools, collaborative text editors and argumentation editors that have been identified as technology enablers for student collaboration (Bouyias & Demetriadis, 2012; Gogoulou, Gouli, & Grigoriadou, 2008; Goldsmith, 2007). Moreover, the number of learning environments that integrate CSCL features with inquiry learning has also increased in the last decade (Gijlers, Saab, van Joolingen, De Jong, & Van Hout-Wolters, 2009). For example, two prominent inquiry-based learning environments, WISE and nQuire, provide learners with opportunities to engage either individually or collaboratively in a series of

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inquiry activities. They facilitate students' conceptual understanding and improve their inquiry skills in science (Linn, Clark, & Slotta, 2003; Sharples et al., 2015). Other successful examples, such as inquiry learning supported by Co-Lab, CmapTool and ModelingSpace, have also been reported to be effective for students' science learning (Avouris, Margaritis, Komis, Saez, & Meléndez, 2005; Novak & Cañas, 2008; van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005). These systems are the representative inquiry-based learning environments with evidence of their learning efficacy.

However, though research on system design for collaborative inquiry abounds, the exploration of student learning in such systems is more limited. Of all the studies on inquiry-based learning in CSCL settings that we have reviewed, most focused on examining student learning outcomes, while the analysis of learning processes in such hybrid learning environments was less prevalent. Even for studies on learning outcomes, little evidence was captured from the interaction between the inquiry process and the CSCL context (Braun & Rummel, 2010; Chang, Sung, & Lee, 2003). Therefore, in this study, we intend to investigate how learning in a CSCL context takes place in an inquiry-based learning environment, and how students' inquiry unfolds and develops with the use of CSCL elements. The system, namely Collaborative Science Inquiry (CSI) learning environment, is a web-based science platform featuring the collaborative inquiry approach. The development of the CSI is targeted at facilitating science instruction and learning at secondary schools (grade levels 7–10) in Singapore.

To tap the benefits with the use of the CSCL approach in an inquiry-based learning environment and to explore the efficacy of such an innovation, we design and study a trial instruction of CSI-supported biology lessons at the Secondary 1 (Grade 7) level. The aims of the study are to: (1) evaluate the effect of the designed CSI lessons on promoting students' conceptual understanding of abstract concepts; (2) trace the progress in students' conceptual understanding at each inquiry phase; (3) identify the factors in students' peer discussion which contribute to the accomplishment of collaborative artefacts in the inquiry activities. The findings will inform the learning design and instruction of the information and communications technology (ICT)-supported collaborative inquiry.

2. Literature review

2.1 Collaborative learning in ICT-supported instruction

Johnson and Johnson (1996) defined collaborative learning as 'the instructional use of small groups so that students work together to maximise their own and each other's learning' (p. 786). Collaboration is not a single mechanism; it often requires all group members to engage on a coordinated effort to provide a joint solution to a problem (Roschelle & Teasley, 1995). Many researchers reached consensus on the value of learning collaboratively with peers for fostering students' understanding of knowledge and critical learning skills (Wang & Burton, 2010). Moreover, to improve the design of collaborative learning so as to achieve better learning outcomes, factors such as group size, patterns of group interaction, teacher scaffolding and technological support provided have been heavily investigated and discussed (Pfister & Oehl, 2009; Yeh, Lo, & Huang, 2011). In these studies, student behaviour in group interaction and teacher behaviour in managing and facilitating group work have become the foci (Lonchamp, 2009; Mercer, Littleton, & Wegerif, 2004).

With the advance of ICT in education and the growing interest in CSCL in recent years, more and more ICT-supported learning environments have integrated CSCL design elements. The design provides students with various opportunities to do collaborative work and meanwhile facilitates teachers to capture more evidence of students' collaboration. The CSCL design elements, for example, the shared diagram editors, shared text editors and whiteboards, are incorporated in the learning system to enable students to accumulate and share resources, and to co-create and improve both diagram- and text-based artefacts (Mühlpfordt & Stahl, 2007). These CSCL elements are complemented with synchronous or asynchronous communication tools (i.e. chat tool), facilitating students to interact and engage in collaborative learning even in distributed places. These elements can also be customised by teachers for designing and enacting different collaborative learning tasks (Lonchamp, 2009).

It is acknowledged that effective collaboration is not easily accomplished if students have no relevant skills (e.g. communication skills, cooperation skills and reflection skills) that can help them to interact well with group members, to plan and organise group work and to make compromises in times of need (Dillenbourg, 1999). Thus, the teacher's role in orchestrating students' collaboration has been frequently discussed in the literature (Dillenbourg, 2013; Roschelle, Dimitriadis, & Hoppe, 2013). In CSCL learning contexts, scaffolding can be provided by the activity design, the teacher or the use of ICT tools. Scaffolding could involve teacher structuring lessons, encouraging reflection on group processes, and monitoring and guiding group interactions (Baines, Blatchford, & Chowne, 2007). Scaffolding scripts consists of instructions/guidelines regarding how group members should collaborate and complete tasks by taking respective roles (Morris et al., 2010). Specifically, such scaffolding aims at structuring the collaborative process by defining sequences of activities, by creating roles for group members and by constraining the mode of intra-group and inter-group interactions (Dillenbourg & Tchounikine, 2007). Thus, to support teachers' better orchestrating of the CSCL class, scaffoldings are embedded in the CSI system.

2.2 Collaborative inquiry learning in science

Recently, a variety of computer-supported inquiry learning environments that guide students to investigate science in real or virtual contexts have been developed. With a focus on identifying the learning designs that proved effective (i.e. inquiry, modelling and visualisation) and the ways in which such designs were combined with CSCL design elements, we review and compare the well-established learning environments (see Table 1). The typical learning environments WISE, nQuire, CmapTool, Co-Lab and ModelingSpace are selected. In a CSCL context, constructing a shared representation, such as a concept map or a scientific model, might be particularly meaningful in combination with inquiry learning tasks. As Table 1 shows, the modelling and visualisation tools are integrated in most applications so as to help students develop subject matter knowledge, epistemological understanding and expertise in the practice of building and evaluating scientific knowledge (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011). Therefore, such design elements that proved beneficial are incorporated in the learning design of the CSI system.

Table 1. A comparison of the design components in established applications.

Component		WISE	nQuire	CmapTool	Co-Lab	ModelingSpace
Inquiry		√	√	×	×	×
Modelling		√	×	√	√	√
Visualisation		√	√	√	√	√
CSCL	Chat tool	√	×	√	√	√
	Shared workspace	×	×	√ (synchronous)	√ (asynchronous)	√ (asynchronous)
	Peer review	√	√	√	√	√
	Coordination tool	×	×	√	√	√
	Social presence	×	√	×	√	×

Besides effective design elements, limitations have also been recognised which CSI learning design sought to improve upon. For instance, in most applications (except for WISE and nQuire), the guided inquiry principle is not embedded. Guided inquiry refers to the inquiry activities which are characterised by a teacher-identified problem and multiple leading questions that point the way to procedures (Wenning, 2005). With the guided inquiry principle, teachers can design the inquiry processes with specific tasks for guiding students' learning in either WISE or nQuire. This has been verified to be useful and effective for science learning (Sharples et al., 2015). However, designs without the guided inquiry principle might not be appropriate and easy for students at lower secondary levels to carry out the inquiry task step by step, particularly when the inquiry activities are conducted collaboratively. Thus, linear inquiry processes are supported in the CSI system to facilitate teachers' task design and students' task completion.

We also find that not all applications include a synchronised and shared workspace to support synchronous collaborative evaluation and improvement of group work. With this design deficiency, students who are distributed might not be able to review, post, modify and elaborate the joint artefacts at the same time with ease (Gutwin & Greenberg, 2002). In addition, most applications (except for Co-Lab and nQuire) lack group management mechanisms, such as social presence, that can track students' presence at and absence from the group work, give students a sense of being together, monitor fellow members' status and progress, and compare those with their own at different inquiry phases. Thus, in the CSI system design, synchronous collaboration and social presence are addressed.

Consequently, following the guided inquiry principle, modelling and visualisation tools which have been proven to contribute positively to science learning are embraced and used collaboratively in the CSI system (Braun & Rummel, 2010; Jackson, Dukerich, & Hestenes, 2008). The CSI inquiry consists of eight phases laid out in an explicit way: Contextualise, Questions and Hypothesise (Q&H), Pre-model, Plan, Investigate, Model, Reflect and Apply (Krajcik et al., 1998; White et al., 2002). The design intends to guide and support lower secondary students to conduct science inquiries. Modelling refers to the construction of scientific models via the use of a drawing-based modelling tool, a concept map tool and a quantitative modelling tool embedded in the Pre-model and Model phases (Lerner, 2007). Furthermore, the system allows the display of various visualisations, such as images, videos and dynamic simulations, to support virtual inquiry. Multiple CSCL design elements, including synchronous editing, synchronous shared workspace, peer review, chat tool and social presence (Lingnau, Hoppe, & Mannhaupt, 2003; Mühlpfordt & Wessner, 2009), are selectively integrated in each inquiry phase. Thus, a key salient feature of the system is the tight coupling of each inquiry phase with relevant CSCL design elements so that each phase can be enacted in a flexible way either through individual or collaborative learning. With this innovative and comprehensive system, we hope effective and meaningful learning will be generated.

3. System overview

3.1. General structure of the CSI learning environment

The CSI system has two functional modules. The teacher module consists of six sections: Profile, Subject Management, Project Management, Simulation Library, Solutions Review and Mailbox. Project Management provides an authoring tool to enable the teacher to establish projects/lessons by creating contextual information, assigning tasks, posing questions and configuring student groups. Simulation Library allows the teacher to import visualisations (e.g. Java applets, videos and flash applications) that are needed for the projects. Solutions Review supports the teacher to access and evaluate students' artefacts (e.g. answers, models and reflections) and chat logs.

The student module comprises four sections: Profile, My Project, Group Management and Mailbox. It allows students to access the assigned project to conduct inquiry activities with their group members. The tasks in the project may include reading and discussing contextual information, postulating hypotheses, manipulating and observing simulations, responding to guiding questions, constructing models and writing reflections at different inquiry phases. See Figure 1 for an interface of the students' 'My Project' section (with annotations of the CSCL features). Students can switch between phases easily by clicking tabs on the tool bar. Help files and manuals are also provided for each inquiry phase.

3.2. CSCL design features in the CSI learning environment

In the CSI system, different forms of online collaborative work are infused into inquiry phases. Specifically, the contextual information in the Overview and

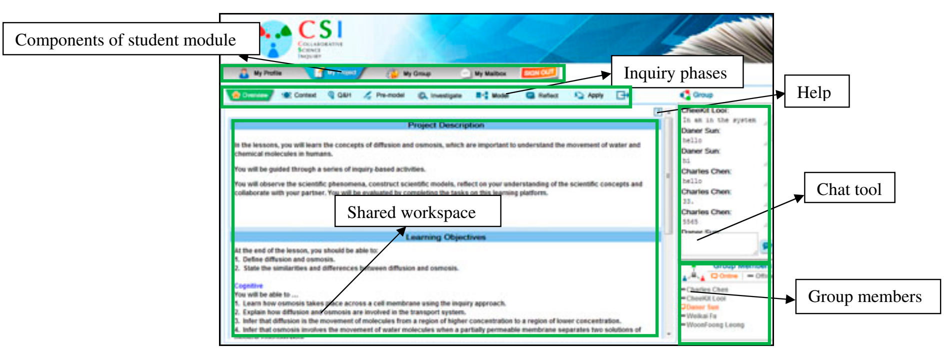

Figure 1. The interface of the student workspace in 'My Project'.

Contextualise tabs allows for sharing and discussion amongst online group members. In Q&H, Plan and Reflect, students are allowed to review, write and revise group members' work synchronously. Moreover, the synchronous construction of the models and communication of the models are enabled at the Pre-model and Model phases. The design is proposed to facilitate students' developing sophisticated understanding of scientific concepts, reasoning skills and reflective learning skills, critical thinking skills, as well as collaborative learning skills (Johnson & Johnson, 1999; Pifarre & Cobos, 2010). Figure 2 illustrates the Pre-model interface. The phase provides two modelling patterns: individual modelling and collaborative modelling. The system also allows for peer review of individual models within group members. With a chat tool, students discuss the learning artefacts synchronously at each inquiry phase.

Overview presents a checklist of tasks to help students to keep track of progress in real time. The online member window shows the status of students' social presence. This facilitates the coordination and collaboration between students from different spatial locations. An email box is attached to both the teacher and student modules for exchanging ideas, materials and other information. In the CSI system, the combination of synchronous and asynchronous collaboration and communication with online learning is proposed to better support learner engagement and improve the quality of student learning better than asynchronous communication does (Giesbers, Rienties, Tempelaar, & Gijselaers, 2014; Johnson, 2006).

4. Methods

4.1. Participants

In the study, the participants were four science teachers and their 201 Secondary 1 students (Grade 7, 12–13-year-olds) from nine classes of a secondary school in Singapore. The teachers had varied science teaching experience (i.e. ranging from three to seven years) and possessed sophisticated ICT-supported teaching skills. Besides, they had joined the project as collaborators since it began in 2009. They participated in weekly meetings to discuss CSI system elaboration, CSI lesson design, implementation and assessment with the researchers and collaborators from the Ministry of Education. They had attained good knowledge of the system design and its underlying pedagogy. Meanwhile, researchers conducted a series of professional development sessions for the teachers for them to better understand the

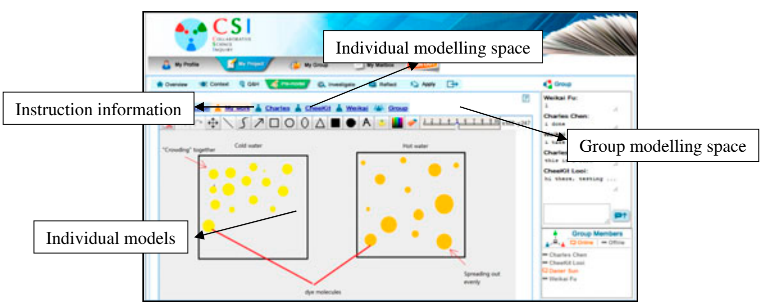

Figure 2. Screenshot of Pre-model interface.

principles of inquiry-based instruction, collaborative learning and teaching strategies of CSI lessons. During the implementation of CSI lessons, most of the time students were organised in pairs (N_{pair}=96), with three groups working in triads.

4.2. CSI lesson design

The teachers together with the researchers identified 'Diffusion and Osmosis' as the topic for the CSI lessons. The CSI lessons sought to develop students' deep understanding of the relevant concepts in diffusion and osmosis. The implementation was conducted over two 50-minute consecutive sessions for each class. Table 2 describes the lesson flow, the proposed teaching strategies, as well as the forms of activities (i.e. individual activity or collaborative activity) of CSI lessons.

Before the class, teachers imported the lessons to the CSI system. In the system, the lesson sequence of 'Diffusion and Osmosis' was arranged in the following order: (Overview) → Contextualise → Q&H → Pre-model → Investigate → Reflect → Apply. When students accessed the project, they first reviewed the contextual information of the project in Overview, and then they were introduced to a story in Contextualise. Students then discussed and formulated hypotheses in response to the

Table 2. The basic information of the lesson flow.

Sequence	Proposed teaching strategies	Forms of activity
Overview	• Introduce learning objectives • Emphasise tasks in the inquiry phases • Remind students of clicking task checklist when work done	
Contextualise	• Present and extract the key information • Pose guiding questions	
Q&H	• Encourage peer discussion • Coordinate students' synchronous writing	
Pre-model	• Ask students to review the 'Instruction' • Observe students' individual modelling activities • Encourage peer review and peer discussion of individual models • Encourage peer discussion and peer work to build models together • Observe the collaborative modelling activities	
Investigate	• Ask the students to observe or manipulate the simulations individually • Encourage peer discussion and answering guiding questions collaboratively • Encourage the students to take the different roles during collaborative activities: editor, reviewer, advisor and reviser	
Reflect	• Emphasise critical reflection on the pre-models and Q&H answers • Encourage the students to reflect upon the process of conceptual changes	
Apply	• Emphasise individual work	

Note:  individual work.
 collaborative work.

questions in Q&H with the use of the online chat tool. In Pre-model, students watched two demonstration videos (the diffusion of red ink in water; and the changes underwent by a raw egg when placed in different solutions) to gain some understanding of the macro-phenomena of diffusion and osmosis. After this, they built two scientific models individually to represent the processes of diffusion and osmosis at the particulate level, and then collaborated with partners to construct the elaborated models. With the intention of capturing more evidence of the students' reasoning and thinking processes, as well as supporting the teacher to monitor the students' progress and to identify students' misunderstandings of the concepts, students were encouraged to interact with their partners for model construction and elaboration via online discussion. The first lesson was concluded with the Pre-model activities. In the second lesson, students played and interacted with three simulations that were aligned with answering the guiding questions based on the observations of the virtual experiments (a. the movement of particles in diffusion; b. the movement of water molecules in osmosis; c. dynamic simulations of diffusion and osmosis) in Investigate. Finally, each student did self-reflection on work done in Q&H, Pre-model, and changes to their conceptual understanding after Investigate. Students were also required to refine and validate their new understanding via the Apply phase.

We expect that, based on the above lesson design, students' conceptual understanding of diffusion and osmosis would develop via the following process: eliciting and applying prior knowledge in Contextualise and Q&H (exposing misconceptions) → knowledge transformation (from the macroscopic view to the microscopic view at the particulate level) in Pre-model (exposing misconceptions and establishing new representations of scientific phenomena) → obtaining new knowledge (at the particulate level) in Investigate (acquiring normative ideas of the scientific phenomena) → revising and improving prior knowledge via Reflect (revising misconceptions) → reinforcing new knowledge through applying in new problematised contexts in Apply (elaborating new understanding).

Hence, the CSI inquiry encourages students to pose a hypothesis, investigate scientific phenomena, construct scientific models, collect evidence and reflect upon the processes in and out of the classroom. This may enhance learner autonomy in learning. It also offers various opportunities for students to discuss solutions, co-construct knowledge, assess artefacts and interact with teachers. In the CSI classroom, teachers are encouraged to play flexible roles to scaffold students' individual writing, reflection and collaborative modelling process in the inquiry phases. They may provide instructions and scripts for doing specific tasks, as well as prompts when students required further explanation of the task and relevant concepts. With frequent use of CSI, teachers' traditional pedagogical approach of ICT use will be shifted to the constructivist approach (Holt-Reynolds, 2000).

4.3. Data sources and analysis

Four researchers conducted the classroom observation. Data sources included pre-test and post-test results, field notes, observation sheets, on-site video and audio transcripts, student learning artefacts and chat logs. The use of different data sources provided complementary information and enabled a more thorough and reliable understanding of students' performance in CSI lessons.

Students' verbal talk which emerged in different inquiry phases was also investigated for obtaining evidence of the relations between students' peer discussions and learning performances. Video and audio transcripts were transcribed and analysed as supplementary data sources for assessing students' performance in the collaborative work, which could provide extra information on students' interaction. Learning artefacts and peer discussion were coded and analysed independently by the first author and another researcher. The inter-rater reliability coefficient of the learning artefacts was $r = 0.93$, and that of the discussion data was $r = 0.89$.

4.4. Instruments and coding methods

4.4.1. Pre-test and post-test results

A pre-test and post-test using identical items were conducted at the beginning and concluding stages of the CSI lessons respectively (10 minutes for each test). The 10-paired questions in tests were built from the previously validated two-tier 'Diffusion and Osmosis Diagnostic Test' (DODT) (Odom & Barrow, 1995). The first tier-A questions asked for direct answers to a given scenario (the 'what' questions), while the second tier-B questions focused on the explanations for the answers provided to the A questions (the 'why' questions). The questions covered all the content of the topic and are at the appropriate difficulty level.[1] Items 1A, 1B, 7A, 7B in tests were the newly developed items, and items 6A, 6B, 7A, 7B, 9A and 9B in the original DODT were removed to make the test fit better with students' cognitive levels and learning objectives of the local science syllabus. The content validity for the test was established by the researchers, collaborators and teachers. Students received one point for each item if they answered it correctly. The total score of the test was 20. A paired-samples *t*-test was conducted to see if there was any difference between the pre-test and post-test results. To further expose students' misconceptions, an item-by-item analysis of the test result was carried out as well.

4.4.2. Responses to Q&H and Apply questions

Students' responses to the open-ended questions in Q&H and Apply, modelling performance in Pre-model and self-reflections in Reflect were further scrutinised to uncover their conceptual change process. A coding method was employed to assess the understanding levels of concepts through categorising the answers to Q&H and Apply questions into five categories. The coding scheme was built on the knowledge integration scoring rubric (Linn & Eylon, 2011), which is an appropriate and effective way to assess how students grappled with multiple and conflicting ideas about scientific phenomena (Liu, Lee, Hofstetter, & Linn, 2008). The categories of understanding levels were refined and modified as follows:

- Level 1 (L_1) – Students have irrelevant ideas and make incorrect links between context and their explanations (incorrect answers).
- Level 2 (L_2) – Students have relevant ideas and make partially correct links between context and their simple explanations (partially correct answers with simple explanations).
- Level 3 (L_3) – Students have relevant ideas and make correct links between context and their simple explanations (correct answers with simple explanations).

- Level 4 (L_4) – Students have relevant ideas and make links between context and their elaborated explanations (correct answers with elaborated explanations).
- Level 5 (L_5) – Students have completely relevant ideas and make links between context and their elaborated explanations, as well as related contexts (correct answers with extended elaborated explanations).

This continuum reveals a progression of conceptual understanding from non-normative ideas, to partially normative ideas, to completely normative ideas, to elaborated ideas and then to extended elaborated explanations. The distribution of students' answers at different levels was calculated and analysed through this coding approach.

4.4.3. Models in Pre-model

A scientific model is defined as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena (Schwarz et al., 2009). Building models reifies the conceptual models. To explore how students identified and described key features or attributes of diffusions and osmosis, and how they related them, we judged the models built in Pre-model by assessing and analysing the model quality. We classified the quality of models into three levels based on a literature review (Grosslight, Unger, Jay, & Smith, 1991; Halloun, 1997; Harrison & Treagust, 2000):

- High Quality Models (H) refer to the models containing accurate description of science conceptions or phenomena that involve model components with basic properties, and reflect interaction between model components.
- Medium Quality Models (M) refer to models with partially accurate description of science concepts or phenomena, which represent parts of model components and describe the possible relations.
- Low Quality Models (L) refer to the models containing inaccurate description of all model components.

The three levels of model quality usually differ in the number of model components, the use of symbols and the description of the relationship among these components (Eilam & Poyas, 2010). In addition, if the models were built at the macroscopic level, they were marked as sublevel '1', while models built at the particulate level were marked as sublevel '2'. As another indicator of the modelling performance, the proportion of the complete models was also calculated and analysed.

4.4.4. Self-reflection in Reflect

In the study, we adopted the principle of reflective thinking and coded the responses to Reflect into four categories: verification, explanation, improvement and critical reflection (Kember et al., 2011). Reflection from low-level to high-level thinking is ranked progressively from 'verification' to 'critical reflection'. The ranking could allow us to probe the level of students' thinking and understanding of their work in the Reflect phase. 'Verification' refers to reflection with simple confirmation of the artefacts; 'Explanation' refers to reflection that interprets the definitions of the concepts, but fails to comment on how to improve the artefacts; 'Improvement' refers to reflection that expresses the ideas on how to improve the artefacts; 'Critical reflection' refers to reflection that involves the critiques and proposals for improvement, as well as further explanation of the conceptual changes.

4.4.5. Peer discussions

Online peer feedback is particularly advantageous in the collaborative discourse as it may encourage students to be adventurous and be more involved (Guardado & Shi, 2007). The coding method was developed based on the principles of good feedback (Nicol & Macfarlane-Dick, 2006). Aligning with these principles, the peer discussions were classified into:

- Task-oriented discourse: clarifies the task specificities, such as procedures, duration and work division.
- Knowledge-oriented discourse: provides necessary information relative to the key concepts, such as definitions, explanations and reasoning.
- Strategy-oriented discourse: provides strategic methods or plans to complete the task.
- Assessment-oriented discourse: provides constructive comments on the work produced.
- Affection-oriented discourse: provides comments with intentions to improve motivations of group members.

We extracted and analysed available peer discussions (taking one sentence as a unit) generated in the chat tool. The calculation of the frequencies of different peer discussions could enable us to recognise students' involvement in the collaborative work, as well as to probe the knowledge-building process (van Aalst, 2009).

5. Findings and discussions

5.1. Pre-test and post-test achievements

In the analysis, the data of students who did not finish both tests were excluded. Altogether 139 valid tests were received. The result of a one-way ANOVA indicates that students' prior knowledge of diffusion and osmosis varied very little among the classes, as F (7, 132) = 2.773, p = 0.01 (the priori alpha level was set at .01). This implies that students started the lessons with about equivalent cognition levels. The paired-samples t-test demonstrates that the post-test scores (M = 12.97, SD = 2.774) were significantly higher than those of the pre-test (M = 10.62, SD = 2.792) (t_{36} = –4.299, p = 0.000). In general, it suggests that CSI lessons enhanced the conceptual understanding of diffusion and osmosis for most of the students.

The item-by-item analysis presents more details of students' conceptual changes before and after the lessons. As the curves in Figure 3 show, the most striking finding is that the correct responses increased apparently in most of items in the post-test. We found that the major conceptual changes occurred in the reasoning of diffusion, dissolving and solutions, the judgement of solution concentration, the identification of osmosis and the effect of osmosis (see the correct responses to

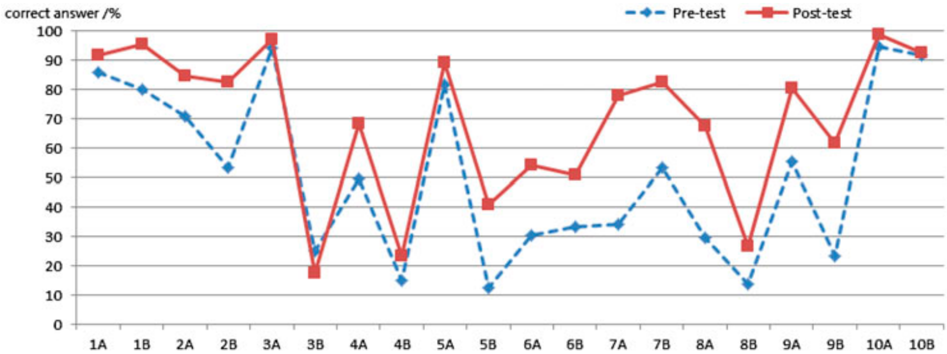

Figure 3. Item analysis on pre- and post- tests.

items 2B, 5B, 6A, 7A, 7B, 8A, 9A and 9B in the pre- and post-tests respectively in Figure 3). This means students had gained significant improvement in the understanding of most concepts in the topic.

In the pre-test, we found that approximately 40.8% of students failed to answer the 'why' questions correctly even though they managed to answer the 'what' questions. This indicates that at this stage students had little understanding about the underlying mechanisms. They simply generated answers based on their intuition or guessing. In other words, their conceptual understanding of diffusion and osmosis remained at the superficial level (Fisher, Williams, & Lineback, 2011). Yet after the lessons, only 15.3% of students had difficulties in responding to the 'why' questions. This reveals that after experiencing CSI lessons, the development of deeper understanding of the target concepts was achieved by the majority of the students. The results of tests could not expose students' learning process, especially for the relationship between their collaboration and conceptual understanding. Thus, further analysis of students' performance at each inquiry phase was conducted.

5.2. Students' performance in CSI inquiry

5.2.1. Q&H

In Q&H, Question 1 (Q_1) asked students to propose a reason for the smell of the cooked fishes from a distance. Question 2 (Q_2) asked students to propose a reason for why the sailors who drank seawater died faster than those who did not drink any water at all. The responses to Q_1 and Q_2 show that students held different prior knowledge of diffusion and osmosis. Q_1 answers were more correct and complete than Q_2 answers (Figure 4).

As Figure 4 shows, Q_1 received 38.6% of L_2 responses and 33.3% of L_3 responses (as students worked in pairs in Q&H, the unit of analysis was the group). This result confirms the findings in the pre-test that students had difficulty in reasoning scientifically and deeply about the basic process of diffusion, as they provided (partially) relevant answers with simple explanations for the reasons for Q_1. Q_2 received less satisfactory responses, with more than half being L_1 responses (56.1%). This is also consistent with the initial finding that a large percentage of students struggled to comprehend osmosis and its mechanism, because osmosis

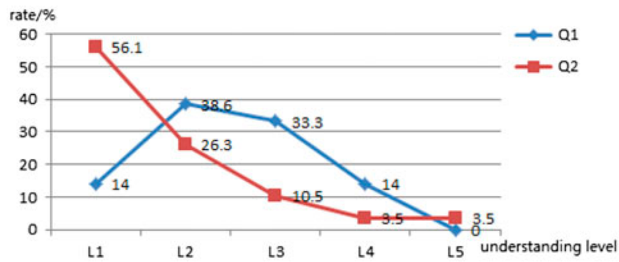

Figure 4. The distribution of students' understanding level of responses to Q_1 and Q_2.

contains more invisible attributes and process (Friedler, Amir, & Tamir, 1987). Only a fraction of students (14% of students provided L_4 responses to Q_1 and 3.5% provided L_4 responses to Q_2) managed to answer them correctly together with elaborated explanations. An interesting finding reveals that although the general performance on responses to Q_1 was better than those to Q_2, a fraction of students (3.5%) performed better in responding to Q_2 compared with Q_1. Based on the analysis of classroom video and audio transcripts, and the chatting information in the chat log, these cases mostly existed among groups in which the pairs interacted with each other (either face-to-face discussion or online chatting) more frequently as we identified.

5.2.2. Pre-model

The variations in students' model drawings are represented by the exemplars shown in Figure 5. Figure 5a exhibits complete understanding of the model components of diffusion. Figure 5b describes the movement of the particles, but fails to label or annotate the components. Figure 5c shows a L_2 model drawing incorrect symbols of all the components of osmosis.

In general, students responded to the individual modelling task positively with a high proportion of work completion (80%). However, 70% of the students failed to build group models (the failures referred to the partially done models and low-quality models). Possible reasons were inferred as follows: (1) Limited class time that negatively affected the group modelling activities. (2) Few opportunities to participate in synchronously collaborative activities in previous lessons. (3) Few collaborative scripts from the teacher at the appropriate time to guide and structure students' collaboration in Pre-model (Onrubia & Engel, 2012).

Data analysis of the resultant models suggests that most students managed to construct individual models at the particulate level but the model quality varied (12.9% of H_2, 54.8% of M_2, 3.2% of M_1, 27.4% of L_2, 1.6% of L_1). Positively, more than half of the students drew the middle quality of diffusion models at the particulate level (M_2 = 54.8%). For osmosis models, H_2, M_2, M_1, $L_{2,}$ and L_1 made up 2.5%, 40%, 7.5%, 35% and 15%. The significant proportion of M_2 models indicates that these students, who had viewed and observed the videos, had acquired appropriate understanding of the micro-phenomenon of osmosis. However, some students failed to identify the model components, which resulted in a number of L_2 models. As we observed and recorded in the classroom, students' active engagement

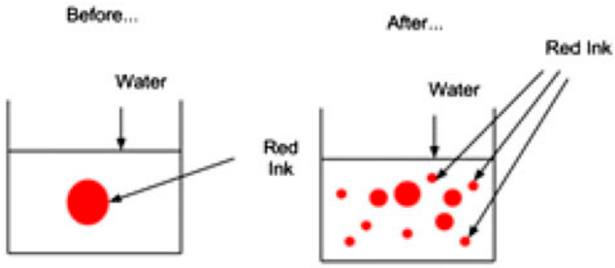

Figure 5a. H_2 model of diffusion.

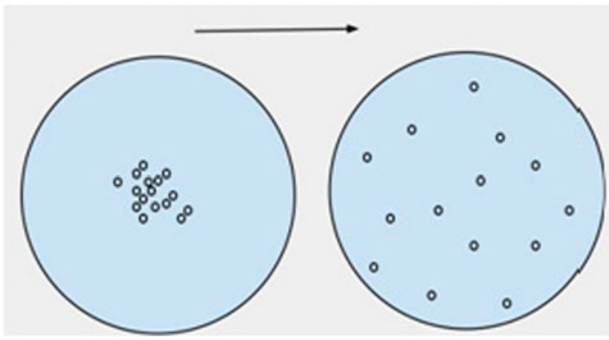

Figure 5b. M_2 model of diffusion.

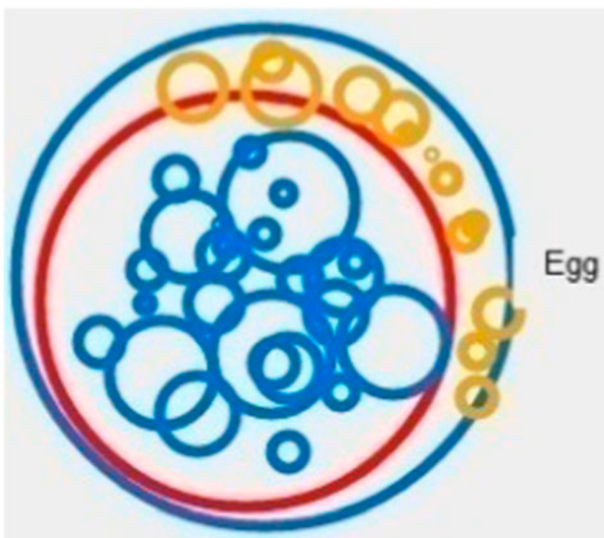

Figure 5c. L_2 model of osmosis.

in peer review and discussion of the models led to improvement in their knowledge of osmosis and diffusion, particularly in the groups who built H_2 models.

5.2.3. Reflect

In Reflect, the task required students to reflect their Q&H answers and models, then provide suggestions for revisions and improvement of the models, as well as explanations for the conceptual changes. Although 30.28% of students only 'verified' their artefacts in Reflect, the rest did reflect upon their artefacts deeply. The 'explanation' (23.33%) reflections indicated that students had achieved better understanding of the target concepts, such as knowledge of the definition, the movement of the particles, and the results of diffusion and osmosis. Students that gave 'improvement' reflections (18.33%) generally thought that they should revise and improve the previous work. Most importantly, 28.06% of students formalised the critical reflections. This suggests that a group of students succeeded in developing more correct and comprehensive understanding as they had managed to convey and present the new understanding through critique, to improve their previous ideas and to explain the improvement. See the following excerpts for some examples:

> A. Verification: 'The models I drew were not animated but still showed how diffusion and osmosis happened.'
>
> B. Explanation: 'Diffusion is the movement of particles from a higher concentration to a lower concentration. Osmosis is the movement of water molecules from a higher water potential to a lower water potential.'
>
> C. Improvement: 'At first, the pre-model of osmosis was just molecules gathering in the middle of a cell. However, after learning more about the cell membrane, the pre-model was changed to molecules going into the cell through the cell membrane.'
>
> D. Critical reflection: 'My pre-model was quite similar to the one in the video clip but that only refers to the diffusion but for the osmosis, I did not draw the process properly as I did not know at first that osmosis involved water molecules (only). I would have changed the picture we drew for the osmosis in a different way like in a beaker separated in half by a partially permeable membrane and place water on both sides but add a solute in one of the sides.'

5.2.4. Apply

Three questions, Q_1, Q_2, and Q_3, were provided for evaluating students' conceptual understanding in Apply. The questions were:

> *Q1:* *Could Elodea or Paramecium from a freshwater lake be expected to survive if placed in the ocean? Explain.*
>
> *Q2:* *Why does salad become soggy when the dressing has been on it for a while? Explain your answer using the concept of osmosis.*
>
> *Q3:* *An effective way to kill weeds is to pour salt water on the ground around the plants. Explain why the weeds die, using principles discussed in the topic.*

The results show that Q_1 and Q_3 received more L_2 (Q_1: 30.3%, Q_3: 30.5%) and L_3 answers (Q_1: 40.5%, Q_3: 34.6%) than L_1 answers (Q_1: 8.9%, Q_3: 15.3%), which reflects that most students could provide partially right answers with different levels of explanations. Few students failed to answer the questions. Further, a number of answers attained L_4 (Q_1: 20.3%, Q_3: 19.6%). The presence of L_4 answers means that these students managed to apply their knowledge learnt from the lessons in the new context. They could explore the macroscopic phenomena by applying the knowledge at the particulate level. However, students seemed to have difficulties in understanding the nature of the dressing relative to the vegetables in Q_2, as most of their answers (56.2%) were at L_1 understanding level.

In this case, it was easier for students to compare between liquid solutions (e.g. ocean, salt water) with hypotonic, isotonic or hypertonic relationships. However, students were hesitant about linking their new knowledge between salad dressing (colloidal mixture) and vegetables (cellular matrix), because no relevant information on colloidal solutions was provided by the simulations.

5.3. Students' performance on the collaborative work

There is a growing awareness that the knowledge construction process is influenced by the social setting in which it takes place. In the CSCL context, discourse interaction can be a window through which to study the knowledge-building process (Gijlers & de Jong, 2005). Thus, through analysing students' discourse that took place when they were doing collaborative activities in CSI lessons, we could get more insights into students' performance in the collaborative inquiry process, and how the peer discussions enabled higher-quality work. The distribution of different categories of peer discussions in inquiry phases is depicted in Figure 6. No affection-oriented discourse was detected in the collaborative activities.

5.3.1. Category A: task-oriented discourse

The task-oriented discourse took up the highest average proportion (42%) of the discussions. This indicates that students were primarily concerned with specifying work procedures and managing the division of labour to complete different tasks in Inquiry; this was especially the case in the Pre-model phase (the proportion of category A was 50.5%). We found that the groups who completed co-constructive models usually involved more task-oriented discourses in peer discussions, which we identified from the chat log and audio transcripts. A considerable proportion of students preferred to discuss specificities about the task with the partners in Reflect (42.8%), Investigate (41.2%) and Q&H (34.2%). We observed that these students

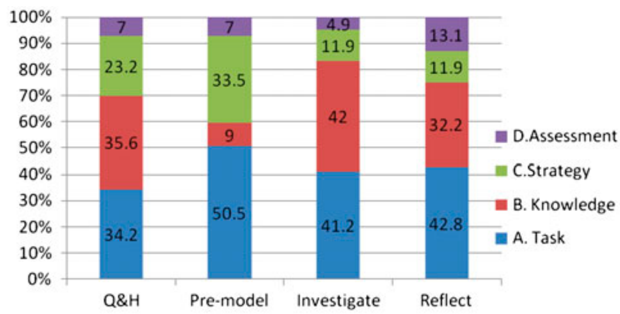

Figure 6. Students' peer discussion during collaborative work in each phase.

performed better in time management, with most of them generating artefacts of higher quality.

5.3.2. Category B: knowledge-oriented discourse

The highest proportion of knowledge-oriented discourse was found in Investigate (42%), followed by Q&H (35.6%) and Reflect (32.2%). The discourse was mostly associated with sharing the definition of key concepts, explaining relevant information or ideas and constructing new knowledge.

Students who had limited prior knowledge of diffusion and osmosis tended to discuss and share their existing knowledge with the team members in Q&H. The proportion of knowledge-oriented discourse (35.6%) was similar to that of the task-oriented discourse in Q&H (34.2%). Students devoted more efforts to negotiating the answer to Q_2. In Investigate, it was noticed that most students used terminologies learnt from simulations to respond to the guiding questions, and they worked together to synthesise the understanding of abstract concepts introduced in simulations. In Reflect, most discourses revealed that students started to revisit the learning experience and to relate the new knowledge to their previous work.

5.3.3. Category C: strategy-oriented discourse

The strategy-oriented discourse took place mostly in Pre-model (33.5%), Q&H (23.2%) and Investigate (11.9%). The discourse provided group members with the resources or methods to complete the tasks. For example, most discourses emphasised the ways to search for relevant information in Q&H. However, some students were observed to return to the textbooks, the Internet or the teacher when the team member(s) failed to reach a consensus on the solution.

5.3.4. Category D: assessment-oriented discourse

The assessment-oriented discourses were rather restricted at all stages of inquiry (7% in Q& H, 7% in Pre-model, 4.9% in Investigate and 13.1% in Reflect). As observed, the proportion of assessment comments increased when students obtained new knowledge and improved conceptual understanding. The proportion in Reflect was comparatively higher as the students were allowed to review each other's reflections and they generally developed more confidence in conceptual understanding at this stage after completing a series of activities.

6. Conclusion

In brief, the CSI system, as a complex learning environment, when integrated with well-designed inquiry activities, presents its potential as a valuable application for enhancing students' conceptual understanding and collaborative learning. In this study, to alleviate the limitation of a non-experimental research design, we base our research findings on examining the test results and reviewing students' performance in the inquiry process. Moreover, students' inquiry and collaboration processes were captured depending on the analysis of learning artefacts and peer discussions in the inquiry phase of the CSI lessons. Our study provides compelling evidence that multiple CSCL design elements deployed in each stage of inquiry facilitate students' collaboration in solving common problems, and their conceptual understanding and collaboration are mutually improved and enhanced. Furthermore, the carefully sequenced task-based learning activities in the CSI system promote students' conceptual understanding in a progressive way.

Specifically, in the CSI classes, students were provided various opportunities to do collaborative work in the inquiry activities. The students participated actively in doing CSI activities, such as watching videos, manipulating simulations, co-constructing models and doing reflections. In particular, students were actively engaged in the Pre-model, Investigate and Reflect phases. This has been substantiated by students' activity performances and their online discussions. In Q&H, students posed common answers to Q_1 and Q_2 in real time. They were active in peer review of the answers, exchanging and discussing the initial ideas, and negotiating task procedures and work division via the chat tool, peer review function and synchronous writing tools. Although the students demonstrated limited prior knowledge at the beginning stage, some good answers were generated by engaging in the active discussion of relevant knowledge. In Pre-model, the shared workspace with an accompanying modelling tool, together with online chatting, promoted students' modelling performance. The way that the students allowed for peer review of individual models, and co-constructing and elaborating the group models in real time, was demonstrated by the good performance in generating medium-quality models (Dillenbourg, 2006).

Further, with active involvement in the strategies-oriented and task-oriented discourses, most students managed to exchange and share the strategies on the modelling task. These strategies enabled the groups to complete their modelling in an effective and rapid way. The finding has been discussed in the work of others that showed that when working in pairs for a logical task, individuals displayed more anticipatory planning and revised their strategies more easily (Blaye & Light, 1995). Research has demonstrated that students were actively engaged and motivated by interacting with simulations (Wieman, Adams, & Perkins, 2008). Our findings also showed that interacting with simulations could eliminate students' misunderstanding. When students were exposed to the new knowledge delivered by the simulations, they exchanged ideas to mutually demonstrate or revise the conceptual understanding. This led to the generation of frequent knowledge-oriented discourses, which in turn further promoted students' knowledge sharing and construction. Lastly, the CSI design encouraged both individual and collective critical reflection and deep thinking by the students. A considerable proportion of critical reflection in the Reflect phase suggested that students consolidated their conceptual understanding. The result was consistent with the statement that collaborative interaction is good for developing critical thinking skills and higher-order thinking strategies (Baines, Blatchford, & Chowne, 2007). This also inspired progressions in conceptual understanding.

In conclusion, the CSI that integrates multiple CSCL elements into distinct inquiry phases in a flexible way accommodates the different demands in collaborative inquiry.

7. Implications and future research

This study contributes to research on collaborative inquiry using computer-supported applications that integrate the CSCL design elements in a guided inquiry process.

The results will in turn inform ICT-supported science instruction. We provide the following suggestions:

(1) Considering that students may have difficulties in completing complex collaborative tasks as some of them may lack collaborative skills in the CSCL context, teachers are advised to emphasise and provide guidance or scripts on group coordination during collaborative editing and co-constructive drawing activities.
(2) Teachers should try to balance students' knowledge needs in the different inquiry phases. For example, the teacher may encourage students to engage more in assessment-oriented discourses when students are exposed to new knowledge. The teachers may guide the students to discuss more about their initial understandings at the beginning stage of the inquiry.
(3) As some of the students may not be able to follow up or fully understand the purposes and procedures of tasks at the beginning stage, teachers can better clarify the purposes and introduce step-by-step procedures when students start to do the assigned activity.
(4) More scaffolding of scientific modelling as follows: initial modelling → model review → model discussion → model revision should be provided for students' modelling activities.
(5) Teachers should examine students' prior knowledge through reviewing their initial artefacts and online chat information, and to identify their misconceptions and general understanding levels. This can serve for the instruction of the new concepts in Investigate.
(6) The Apply questions should be linked to students' learning experiences acquired during Investigate.
(7) To facilitate students' peer discussion, guiding questions should be posed in Investigate.

For future research on the CSI learning environment, we will investigate quantitatively the relation between students' learning outcomes and their discourses generated in the activities. More emphasis will be paid to the teacher factor in the enactment of CSI lessons, to unpack the relationships between students' performances and teachers' teaching styles and teaching strategies, as well as teacher beliefs, through comparing teacher performance in different CSI lesson implementations.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Note

1. The test can be retrieved from: https://sites.google.com/site/futureschoolcsinquiry/pedagogical resources/diffusion_ osmosis_test.

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