Collective Knowledge Advancement and Conceptual Understanding of Complex Scientific Concepts in the Jigsaw Instruction

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Abstract: We examined jigsaw instruction related to the human immune system at a high school from the perspective of knowledge creation. Collective knowledge advancement was analyzed using socio-semantic network analysis (SSNA) and in-depth discourse analysis. Their conceptual understanding was collected through pre- and post-testing and evaluated by using the structure–behavior–function framework. SSNA revealed that higher conceptual understanding was related to improved collective knowledge advancement. Further in-depth discourse analysis clarified that students who acquired higher conceptual understanding engaged in shared epistemic agency through productive regulatory processes to promote their collective knowledge advancement. Based on the results, we discuss and propose scaffoldings for more students to engage in productive collaboration in jigsaw instruction.

Keywords: collective knowledge advancement, shared epistemic agency, regulation of collaboration, structure–behavior–function framework, jigsaw instruction

Theoretical background

Inquiry into collective knowledge advancement

In the knowledge-creation metaphor of learning (Paavola & Hakkarainen, 2005), students are expected to be involved in knowledge creation practice through collaborative construction of knowledge objects (Bereiter, 2002). Regarding creating knowledge in the classroom, Scardamalia (2002) discussed collective cognitive responsibility for contributing ideas toward collective knowledge advancement. She defines intentional engagement in collective knowledge advancement as the epistemic agency and proposes this agency as a new goal for instruction in the knowledge age (Scardamalia, Bransford, Kozma, & Quellmalz, 2012). Damşa, Kirschner, Andriessen, Erkens, and Sins (2010) further propose shared epistemic agency focusing more on the group-level agency. Through in-depth discourse analysis, Damşa et al. found that students in collaborative groups engage in the wholly joint epistemic actions of (1) being aware of their lack of knowledge, (2) alleviating this lack of knowledge, (3) creating shared understanding, and (4) generative collaboration. To regulate their joint epistemic actions, students were also found to engage in (1) projection by setting goals and creating joint plans, (2) regulation by monitoring and reflecting on their advancement, and (3) relation by transcending conflicts, redirecting critical feedback, and creating space for others' contributions.

A new computational approach to collective knowledge advancement

In CSCL research, there have been discussions on the advantages of using social network analysis (SNA) to investigate collective knowledge advancement and learner engagement (e.g., Martinez et al. 2003; Reuven et al. 2003). De Laat et al. (2007) outlined an approach to synthesizing and extending comprehension of CSCL teaching and learning processes to balance SNA, content analysis, and critical event recall. In this complementary approach, SNA was used to study interaction patterns within a networked learning community, and to study how learners share and construct knowledge. They concluded that including SNA in any multi-method approach is advantageous, because doing so provides researchers and learners with tools for illustrating comprehension and cohesion of group activities, and because it provides researchers a method for selecting appropriate groups to study. Several studies have used SNA, especially in as a knowledge-creation metaphor. Over three years, Zhang et al. (2009) implemented a complementary approach that used SNA to visualize and compare classroom collaboration among fourth-grade elementary school students in a CSCL environment designed to support knowledge building. An analysis of online participatory patterns and knowledge advancement indicated that this learning process effectively facilitated knowledge advancement through critical changes in organizations within the classroom, from fixed small groups in the first year of the study to appropriate collaboration through the dynamic formation of small teams based on emergent goals.

We extended the potential of SNA by describing a different type of network, socio-semantic network analysis (SSNA). Ordinary SNA illustrates the social patterns of learners, namely, their social network. As de Laat et al. (2007) suggested, this approach is thus informative when examining developments or changes in the participatory structure of a community. However, several studies argued that existing social network models are unable to examine how collective knowledge advances through learner collaboration (Oshima et al., 2007; Schaffer et al., 2009). Instead, we used a procedure similar to ordinary SNA but proposed a different type of social network, one based on the words learners use in their discourse in a CSCL environment. We compared this socio-semantic network—in which words were selected as nodes representing learners' knowledge or ideas during a discourse on a study topic—with a network of words from the discourse of a group of experts on the same topic. The results showed remarkable differences in the collective knowledge of elementary school students and experts regarding the words centered on the networks. We concluded that SSNA could provide a new representation of community knowledge building, enabling researchers to adopt a new complementary assessment technique for investigating models of knowledge-building communities. In recent years, this SSNA approach has been adopted in CSCL studies to analyze student roles in collaboration and to detect productive interaction patterns (e.g., Ma et al., 2016; Oshima, Oshima, & Matsuzawa, 2012).

Conceptual understanding of complex scientific concepts

In knowledge-creation practices, learners take on complex tasks and comprehension of phenomena. Complex systems are defined as multiple levels of organizations locally interacting with one another such as financial economies and weather systems (Wilensky & Jacobson, 2013). Many students have difficulty mastering such complex subjects, despite their importance. One reason for this is that these concepts conflict with prior experience. Students usually have a "centralized" mindset and tend to provide explanations that assume central control and simple causality. In an interview study, Jacobson (2001) found that undergraduate students are more likely to generate simple causality, central control, and predictability in comparison with experts, who exhibit decentralized thinking of multiple causes as stochastic and equilibration processes.

Hmelo-Silver and Pfeffer (2004) proposed the structure–behavior–function (SBF) framework for assessing student understanding of complex systems. While the SBF framework has been used to examine the design of physical devices, they applied it to explaining student understanding of multiple interrelations and the dynamic nature of complex systems. To assess student understanding of an aquarium as a complex system, for instance, Hmelo-Silver and Pfeffer (2004) used the SBF framework as follows: Structures are elements of a system, and in an aquarium, there are fish, plants, and a filter. Behaviors represent how system structures achieve their purpose, such as filters that remove waste by trapping large particles, absorbing chemicals, and converting ammonia into harmless chemicals. Finally, functions express why an element exists within a given system, that is, the purpose of a system element. For example, the filter removes aquarium byproducts. They studied verbal responses and pictorial representations by middle school students, preservice teachers, and experts, and found that novices focused on perceptually available, static system components. Experts, on the other hand, focused more on interrelation among structures, functions, and behaviors. The results suggested that the SBF framework could be a useful formalism for understanding complex systems.

Research purpose

This study examined how high school students engage in collective knowledge advancement through collaboration in jigsaw instruction (Brown & Campione, 1996; Miyake & Kirschner, 2013) and how their collective knowledge advancement is related to their learning outcome. Although studies have demonstrated that jigsaw instruction is effective for facilitating conceptual understanding (e.g., Miyake & Kirschner, 2013), few studies have shown how learners engage in collective knowledge advancement during collaboration. Through our design-based research on an immune system lesson (three class hours), we approached students' collective knowledge advancement by applying a multivocality approach (Suthers et al. (Eds.), 2013). First, we conducted a socio-semantic network analysis (SSNA) for numerically and visually representing collective knowledge advancement and comparing group performance based on their learning outcome, as evaluated by the SBF framework (in pre- and post-testing). We also conducted in-depth discourse analysis from the perspective of shared epistemic agency and the regulation of collaboration to examine how students interact with one another in collective knowledge advancement.

Methods

Student sample

Thirty-nine tenth grade students at a high school in Japan participated in this study as part of their regular curriculum. The high school is well-known and highly ranked in its district as a college prep school. Most graduating students go on to university. A science teacher with a Ph.D. in biology and more than ten years of teaching experience taught the students.

Lesson unit design

Activity structure of collaborative learning: Constructive Jigsaw instruction (Figure 1)

We applied constructive jigsaw instruction (Miyake & Kirschner, 2013) in this study. In the jigsaw instruction, three students in a group were given a challenge such as "Can you explain how vaccinations protect us from infections?" then provided three study documents, each of which was necessary for solving the challenge. In the first phase of collaborative learning, one student from each group gathered to form an *expert* group and worked on their allocated materials over 1.5 lesson periods (each lesson period was 50 min.). After the expert group activity, students returned to their original group (the *jigsaw* group), where students had different pieces of knowledge. They were encouraged to share and integrate their individual knowledge to solve the challenge problem in the jigsaw group activity. This jigsaw activity took another 1.5 lesson periods. Group composition in the both group activities was designed by the teacher.

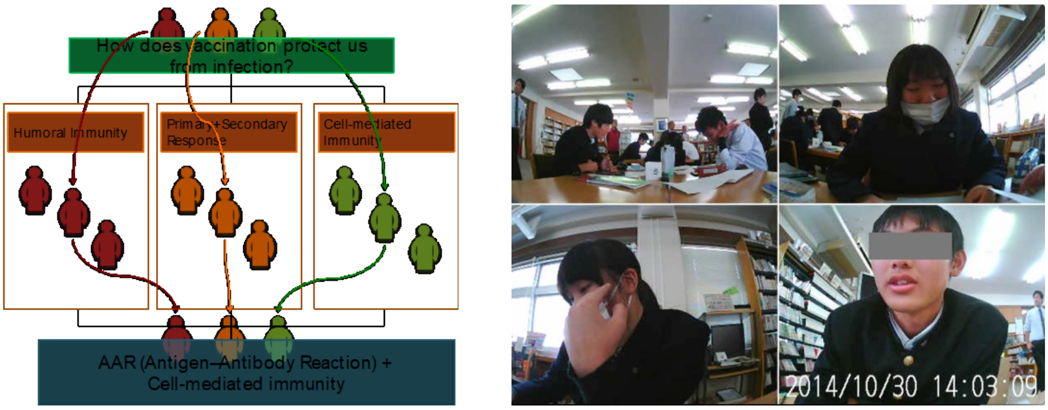

Figure 1. Jigsaw Activity Structure in the Immune System Lesson (Left) and a Snapshot of Recorded Data (Right).

Study documents

We first identified what knowledge and principles were covered in the school textbook. Figure 2 shows the SBF framework for the immune system as described in the textbook. We then discussed with the collaborating teacher how to separate the content into pieces of knowledge given to students in expert activities based on three key functions (the three areas separated by dashed lines in Figure 2): *humoral immunity*, *primary and secondary response*, and *cell-mediated immunity*.

Study design

Pre- and post-tests

Before and after the lesson unit we applied pre- and post-tests to evaluate learning outcomes. Students were individually asked about their understanding of how the human immune system responds to vaccination. They were given a worksheet with a printed question, on which they could write or draw their ideas. The pre-test was conducted during the class period right before the lesson started. The post-test was conducted right after the lesson finished. Each test took one lesson period. Thirty-five students completed both tests and were further analyzed.

Process data collection

Student conversations during expert and jigsaw group activities were video recorded by a device with four cameras and an omnidirectional microphone placed at the center of the table (right half in Figure 1). Student conversations were transcribed and used for SSNA. We used transcriptions of the jigsaw group activity to examine how students exerted agency in advancing their collective knowledge with three pieces of knowledge acquired in their expert group activity.

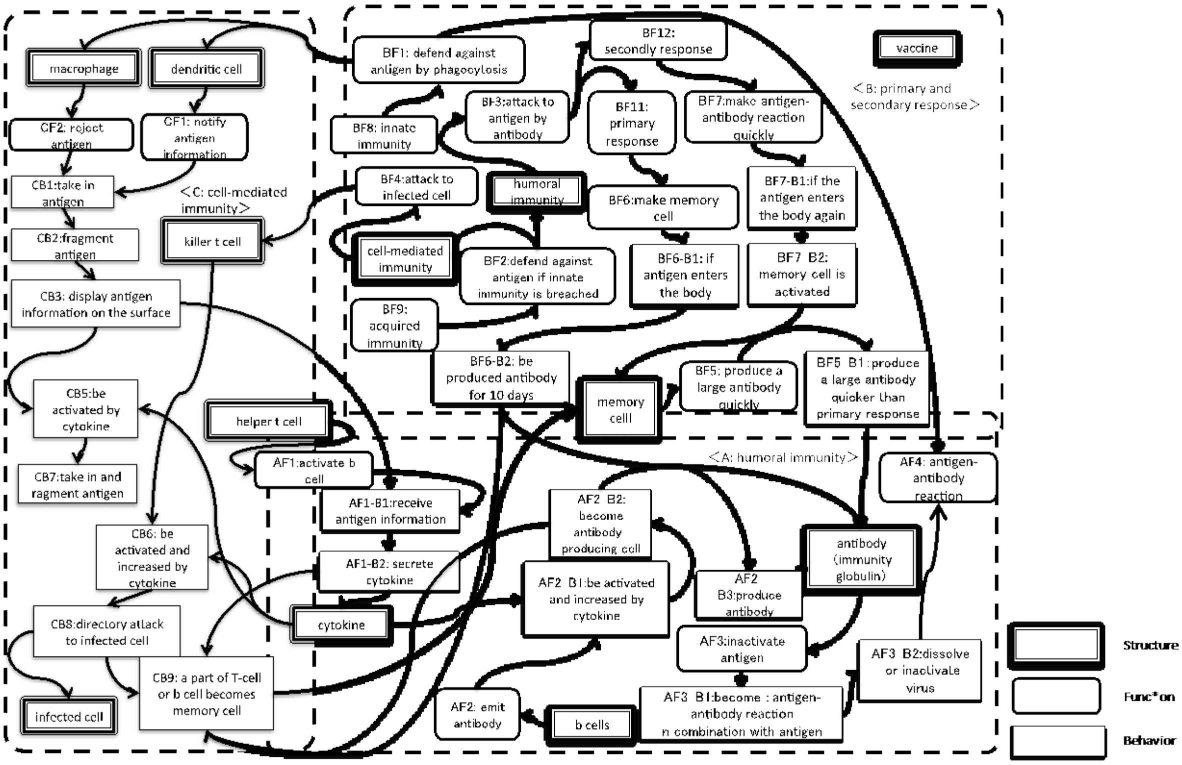

Figure 2. Structure–Behavior–Function Framework of the Human Immune System.

Analysis procedure

We first investigated how students developed their biological understanding of the immune system as a complex system. To do so, we analyzed their writing and drawings on the pre- and post-test. Student SBF frameworks were categorized into the following types: When student explanations of how the immune system works considered the relationships among structures, their behaviors, and functions as described in a specific document (A, B, or C), we evaluated that they successfully constructed their understanding of the document. We did not count fragmented descriptions of structures, behaviors, or functions where connections were not identified. Based on this criterion, students were categorized as having (1) no understanding, (2) single-document understanding, (3) partially integrated understanding between two documents, or (4) fully integrated understanding across three documents. Referring to the SBF framework of the immune system, the first and second authors independently evaluated ten randomly selected students' SBF frameworks based on their explanatory discourse and pictures in each of the pre- and post-tests. Cohen's Kappa coefficient for the agreement between the two raters was 0.92. Disagreements were resolved through discussion. The first author evaluated the remaining data. Because no students demonstrated knowledge of the SBF framework of the immune system in the pre-test, we focused on their SBF frameworks in the post-test for analysis.

To analyze students' collective knowledge advancement, we next focused on discourse in the jigsaw group. Students on average engaged in discourse exchange 358.5 times in jigsaw groups (SD = 211.8). One reason for paying attention to the jigsaw activity was that students were expected to actively engage in creating new ideas by integrating their knowledge from three documents. To visualize and computationally investigate collective knowledge advancement, we conducted SSNA by the following procedure: We assumed that we could represent the state of collective knowledge as clusters of vocabulary that students used in their discourse. For investigating their collective knowledge, we selected words used to represent *structures* and *functions* of the immune system in the SBF. The socio-semantic network of vocabulary refers to meaningful links between words in exchanges. When students used words in their exchanges, we assumed that they were attempting to create meaningful links between words. We used 23 nouns representing *structures* and *functions* in the SBF framework of the immune system. We then used an application called KBDeX (http://www.kbdex.net) to SSNA to calculate the transition of the total value of degree centralities of nodes in the network across discourse exchanges, following the method of previous research (Oshima et al., 2012).

Our SSNA approach requires complementary discourse analysis to examine how students exerted shared epistemic agency through regulatory processes of collaboration in their collective knowledge advancement. We therefore also conducted an in-depth analysis of discourse segments related to pivotal points of collective knowledge advancement as a drastic increase in the total value of degree centralities.

Results and discussion

Student learning outcomes after the jigsaw activity

We found that ten students fully integrated SBF understanding and eleven students did so partially. Eleven students indicated the understanding of a single part of a learned document and three did not sufficiently learn any piece of SBF. Chi-square analysis of student frequencies across three types of learning outcome (fully or partially integrated, the single document, or no understanding) showed significance ($\chi^2 = 13.944$, $df = 2$, $p < .05$), and that the proportion of students having integrated SBF understanding was higher than students with no understanding. These results suggest that the jigsaw activity in practice facilitated student integration of knowledge through collaboration, but group differences remained in the learning outcomes.

Group differences in collective knowledge advancement between high- and low-outcome groups

Based on the SBF framework evaluation of conceptual understanding, we categorized twelve groups as high or low learning-outcome groups. In the high learning-outcome groups, all members acquired fully or partially integrated conceptual understanding of documents. Low-outcome groups were mixed in their understanding. Figure 3 shows the transitions of total values of degree centralities. The total value of degree centralities represents how dense and structured a network (of words in this case) could be. This measure has been used as a typical index to detect collective knowledge advancement (e.g., Oshima et al., 2012). We found that the values quickly increased then finally exceeded 10.0 in the high-outcome groups, whereas the values stayed low and slowly increased across discourse exchanges in the low-outcome groups. The results suggest that students in the high-outcome groups engaged in collective knowledge advancement more quickly and sustainably.

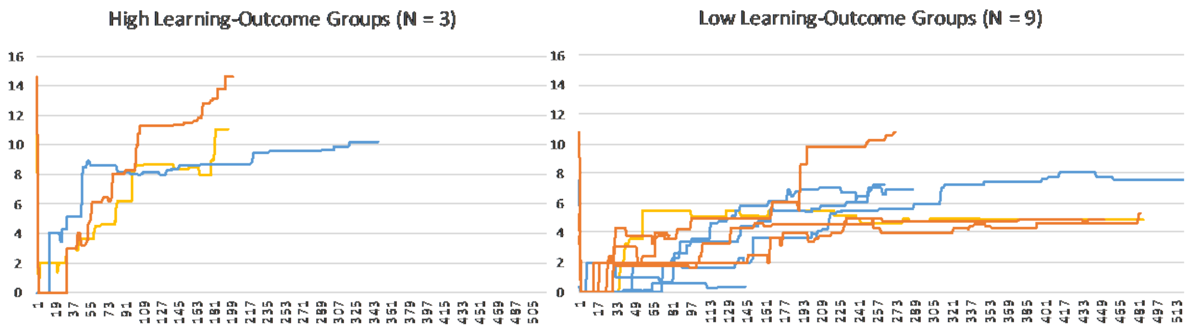

Figure 3. Transitions of Total Values of Degree Centralities Through Discourse Exchanges by High Learning-Outcome (left) and Low Learning-Outcome (right) Groups.

We further analyzed segments of student discourses for clarifying how they engaged in collective knowledge advancement. We first present one example of discourse segments by a high learning-outcome group (The original discourse was in Japanese and translated into English by the first author. SSNA vocabulary is in bold.).

Student A (156)	So, what did we say? They are trapped and broken into smaller pieces, and their **antigenic** information is transmitted to **helper T cells**. Next, **helper T cells** emit a substance called **cytokine**.
Student B (157)	**Cytokine**?
Student A (158)	Yeah, **cytokine**. Oh, you [student B] put this [**cytokine**] down twice [on the worksheet].
Student B (159)	Twice?

Student A (160) Oh, never mind. Just put down "**cytokine.**" This is emitted. Then, draw an arrow from **T cell** to **B cell**, please. [Student A told B to draw an arrow on the worksheet.]

Student B (161) T and B?

Student A (162) I wonder how we can describe this... Well, **T cells** propagate. Would you [student B] shorten the space here [pointing at an area in the worksheet] a bit?

Student B (163) Propagate?

Student A (164) Yeah, **T cells** do propagate.

Student C (165) Wait a minute. How about **memory T cells**? Are they part of the activated cells?

Student A (166) **T cells** propagate. Then, how about these [**B cells**]? These [**B cells**] create **antibodies**.

Student B (167) ... create **antibodies**.

Student A (168) and, some will become **immunological memory cells**,

Student B (169) **Immunological**?

Student A (170) **Immunological memory cells**. Here, look [at a picture in their documents]. Some of them remain as **immunological memory cells**. Then, we go to **the secondary response**.

Student B (171) **The secondary response**?

Student A (172) Through **the secondary response**, when viruses come into our body...

Student B (173) OK, they come into us.

Student A (174) I wonder if we have to make two lines here [pointing an area in the worksheet], too. **Immunological memory cells** react to the viruses. **T cells** also react to them. **T cells** then become **killer T cells**. **Killer T cells** propagate. On no, we need more space [in the worksheet] to write this down... Then, this [**B cells**] emits **antibodies** to **antigens**. This is called **antigen–antibody response**.

From the perspective of shared epistemic agency, students mostly engaged in *creating shared understanding* of how the immune system works. Student A played a central role in externalizing shared understanding through monitoring confirmation by others (B and C). Student B had the role of recording their ideas on the worksheet, and so frequently *revoiced* student A's externalizations (turn #159, #161, #163, #167, #169, #171, and #173). Student A interacted with B to co-create an external knowledge object in the worksheet. In contrast, student C had the different role of going beyond just *creating shared understanding* to *generative collaborative actions* by up-taking student A's argument (turn #165). Student C might attempt to improve student A's idea based on self-understanding by asking important questions from a different perspective (e.g., "Wait a minute. How about memory T-cells?"). Within this discourse segment, students A and C were more engaged in *generative collaborative actions*, whereas student B was engaged in *creating shared understanding*. Students A and C revealed fully integrated understanding in the post-test and B did partially integrated.

The next example is from a low-outcome group. They were discussing how to write their ideas on their iPad. They did not use their worksheet we introduced.

Student E (63): So, what's next? We acquire **immunity** systems. [looking at a picture in their documents]

Student D (64): We learned two **immunity** systems.

Student E (65): Yeah, **cell-mediated immunity** and **humoral immunity** around here? [pointing an area in a picture]

Student D (66): **Humoral immunity**.

Student E (67): **Humoral immunity**. We have to make a sentence.

Student F (68): Yeah, we should.

Student E (69): So, when something like **viruses** comes into our body, ⋯

Student D (70): Yes.

Student E (71): **Macrophage** and **white blood cells** capture and decompose the **antigens** like **viruses**. This is the **innate immunity** system.

Student D (72): This is the most..

Student E (73): This is the most primitive and works a lot in our body. Sounds good [to others]?

Student D (74): Let's go on.

Student E (75): Uh,

Student D (76): Why do not we just follow this [picture in their studied document]?

Student E (77): I agree. So, we see "extinction" here. [pointing on an area in the document]

Student D (78): We do not mind how to say. How about "extermination"?

Student F (79): Shall we copy them? Just like them?

Student D (80): Can we use arrows in writing on the Pad? [typing on an iPad]

Student E (81): We can go from the left to the right. So, this should be the first.

Student D (82): OK, this is the first.

On the contrary to the high learning-outcome group, students in this low learning-outcome group could not sustain their shared epistemic agency during collaboration. In lines #63–#73, they engaged in *creating shared understanding*. They were collaboratively constructing sentences for their explanatory discourse. Their discourse, however, was digressed from their shared epistemic agency by student D's turn (#76 "Why do not we just follow this [picture in their studied document]?"). Student D proposed to transform the epistemic goal of their collaboration into the performance goal, and this proposal was quickly accepted by the other students (#77 and #79). Students D and E attained single-document understanding and F did partially-integrated in the post-test.

Discussion

SBF assessment revealed that our design of student collaboration was partially successful in facilitating conceptual understanding. Significantly, most students succeeded in acquiring integrated SBF understanding, but more than ten students did not. At the group level, we found large group differences in learning outcomes. Only three groups revealed integrated conceptual understanding among all group members. In the other nine groups, some acquired integrated understanding while others attained single-document understanding or none. These results suggest group differences in collective knowledge advancement and individual differences in engagement in shared epistemic agency.

SSNA clearly demonstrated group differences in the collective knowledge advancement. In the high learning-outcome groups, students quickly engaged in advancing their knowledge and sustained it. In contrast, students in the low learning-outcome groups were slow starters. They did not discuss their ideas by linking one another and did not reach the high level of consolidation of ideas. Our analysis of group discourse in jigsaw activity supported the results from SSNA. For fully integrated SBF students in the high learning-outcome group, the knowledge object was a basis for *generative collaborative actions* by monitoring others' ideas. Neither directly operated the object, but instead monitored the inscription. In contrast, for another partially integrated SBF student, the same knowledge object was a product for *creating shared understanding*. That student was totally responsible for creating the product, and so had to devote mental power toward correctly inscribing ideas through frequent *revoicing*. This difference in knowledge object-oriented actions came from co-regulation and socially shared regulation. Collaboration by two fully integrated SBF students was socially shared, whereas a partially integrated SBF student was co-regulated by another student.

Through examination of student collaboration in jigsaw instruction from the knowledge-creation perspective, we found how students engaged in collective knowledge advancement when successfully acquiring deep conceptual understanding. As the preceding research (e.g., Damşa, 2014) suggests, epistemic agency played a key role in successful collaboration. A new finding suggested in this study is interaction between epistemic agency and multi-layered regulatory processes in collaboration mediated by knowledge objects. For every student to engage in productive collaboration, the knowledge object should be the basis for further epistemic actions. How to produce and share knowledge objects could be further designed from the perspective of regulatory process in collaboration for productively stimulating student epistemic agency.

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