Collective Knowledge Advancement through Shared Epistemic Agency: Socio-Semantic Network Analyses

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Abstract: This study examined how high-school students engage in collective knowledge advancement through shared epistemic agency during jigsaw instruction, and how their collective knowledge advancement (through shared epistemic agency) relates to learning outcomes. To achieve this, we applied a double-layered socio-semantic network analysis (SSNA). In the first layer of the analysis, we conducted an SSNA to numerically represent collective knowledge advancement and to compare group performances between different levels of learning outcomes. In the second layer, we carried out an Epistemic Network Analysis to examine the relationship between students' shared epistemic agency and learning outcomes. The results revealed that high learning-outcome groups were engaged in epistemic actions to generate new ideas; this led them to quick and sustainable knowledge advancement.

Research purpose

This study has analyzed the way in which high-school students engage in collective knowledge advancement through shared epistemic agency (Damşa et al., 2010) during jigsaw instruction (Brown & Campione, 1996). It has also investigated the extent to which this collective knowledge advancement relates to learning outcomes. Although studies (e.g., Miyake & Kirschner, 2013) have demonstrated that jigsaw instruction is effective in facilitating conceptual understanding, few studies have shown how learners engage in collective knowledge advancement during collaboration (Oshima, Oshima & Matsuzawa, 2012). The present study explored the students' collective knowledge advancement by applying a double-layered socio-semantic network analysis (SSNA). In the first layer of the analysis, we conducted an SSNA to numerically and visually represent collective knowledge advancement and to compare group performance based on learning outcomes, as evaluated by the SBF framework (in pre- and post-testing). In the second layer, we carried out an Epistemic Network Analysis (ENA) (Shaffer, 2017) to examine the relationship between epistemic frames of shared epistemic agency and learning outcomes.

Theoretical background

Inquiry into collective knowledge advancement during jigsaw instruction

Many studies have attempted to design learning environments to facilitate students' collective knowledge advancement. One such instructional method is jigsaw instruction. In jigsaw instruction, learners engage in two different phases of an activity. In the phase known as the "expert group activity," learners work collaboratively on the same materials. Collaboration in the expert group facilitates constructive interaction among the learners (Miyake, 1986), enabling them to develop their own understanding by mutually monitoring each other's ideas from different points of view. After learning their materials during the expert group activity, learners join the jigsaw group activity, where those who studied different materials gather to integrate different sources of knowledge collaboratively. In the jigsaw group activity, learners are predicted to engage in productive interaction within multiple zones of proximal development, depending on the different knowledge sources (e.g., Brown & Campione, 1996). With respect to any one component of the learning activity, one student is an expert on that domain and teaches the other group members. This teaching–learning process is repeated multiple times.

Although studies have demonstrated that jigsaw instruction is effective in facilitating conceptual understanding and collective knowledge advancement (e.g., Miyake & Kirschner, 2014), few studies have examined in detail the process through which learners take responsibility for contributing to collective knowledge advancement through collaboration, i.e., shared epistemic agency. In relation to the knowledge-creation metaphor of learning (Paavola & Hakkarainen, 2005), students are expected to practice knowledge creation through collaboratively constructing knowledge objects (Bereiter, 2002). Scardamalia (2002) has discussed intentional engagement in collective knowledge advancement as epistemic agency— proposing this agency as a new goal for instruction (Scardamalia et al., 2012). Damşa et al. (2010) have also argued in favor of shared epistemic agency, focusing more on group-level agency. Through an in-depth discourse analysis, Damşa et al. (2010) found that students in collaborative groups engage in the wholly joint epistemic actions of (1) being aware of their lack of knowledge, (2) alleviating the lack of knowledge, (3) creating a shared understanding, and (4) generative collaboration. To regulate their joint epistemic actions, students have also been found to engage in (1) projection by setting goals and creating joint plans, (2) regulation by monitoring and reflecting on their advancement, and (3) developing relations by transcending conflicts, redirecting critical feedback, and creating space for others' contributions. Studies by Scardamalia (2002) and Damşa et al. (2010) suggest that we need to analyze collaboration as knowledge creation, based on at least two layers of collective knowledge advancement: (1) how learners' ideas are improved through their collaborative discourse (i.e., idea improvement) and (2) how learners engage in improving their ideas collectively (i.e., shared epistemic agency).

Double-layered socio-semantic network analysis

In this study, we propose using two layers of socio-semantic network analyses (SSNA). Recent studies (Oshima et al., 2012; Shaffer et al., 2009) have argued that existing social network models are unable to examine the way in which collective knowledge advances through learner collaboration. Two lines of research have been used to solve this problem. The first approach is to apply a procedure that is similar to an ordinary SNA to examine a different type of social network: a socio-semantic network based on the words that learners use in their discourse. Connections between words are assumed to represent clusters of ideas; the change in the socio-semantic network structure over time is examined both visually and computationally to investigate how a group of students engages in collective knowledge advancement (e.g., Ma et al., 2016; Oshima, Oshima & Fujita, 2018; Oshima et al., 2017). The second approach is another SSNA, based on epistemic frame theory, called Epistemic Network Analysis (ENA) (Shaffer, 2017). ENA is an algorithm that identifies and calculates connections among elements in coded data and visualizes them in dynamic network models that illustrate their structure and strength over time. With ENA, researchers can qualitatively and quantitatively examine cultural practices that participants engage in, such as engineering projects (e.g., Svarovsky, 2011), through their discourse. The present study uses both approaches to investigate different layers of student activity. We have carried out a vocabulary network analysis of their collective knowledge advancement and an ENA to assess their shared epistemic agency.

This study combines the approaches and findings of our previous studies, which examined students' collective knowledge advancement (Oshima et al., 2017), with a further ENA by coding the same discourse data from the perspective of shared epistemic agency.

Conceptual understanding of complex scientific concepts

Through collective knowledge advancement, learners are expected to engage in complex tasks and comprehension of phenomena. Complex systems are multiple levels of organizations locally interacting with one another, such as financial economies and weather systems (Wilensky & Jacobson, 2013). Studies have revealed that students have difficulty mastering such complex subjects, despite their importance. One reason for the difficulty is that the complex concepts conflict with learners' prior experience. They usually have a "centralized" mindset and tend to favor explanations that assume central control and simple causality. In his interview study, Jacobson (2001) found that undergraduate students were more likely than experts to generate simple causality, central control, and predictability; by contrast, the experts exhibited decentralized thinking about multiple causes, such as stochastic and equilibration processes.

Hmelo-Silver and Pfeffer (2004) have proposed a structure–behavior–function (SBF) framework for assessing different levels of student understanding of complex systems. To assess students' understanding of an aquarium as a complex system, for instance, they used the SBF framework in the following way. Structures are elements of a system; in an aquarium, there are fish, plants, and a filter. Behaviors represent the way in which system structures achieve their purpose; for example, filters 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—in other words, they express the purpose of that system element. For example, the filter removes aquarium byproducts. When researchers studied the verbal responses and pictorial representations of middle-school students, preservice teachers, and experts, they found that novices focused on perceptually available, static-system components. Experts, on the other hand, focused more on interrelations among structures, functions, and behaviors. These results suggest that the SBF framework could be a useful formalism for understanding complex systems.

The present study has used this framework to assess high-school students' conceptual understanding of the human immune system as a complex system. Both before and after the lesson, we asked the students to explain how vaccination protects us from infection by using their knowledge of the human immune system.

Methods

Student sample

Thirty-nine tenth-grade students at a high school in Japan participated in this study, as part of their regular curriculum. A science teacher with a Ph.D. in biology and more than ten years of teaching experience taught the students.

Lesson design

Structure of the collaborative learning activity: Jigsaw instruction

Twelve groups were formed with three or four students in each and were given a challenge, such as "Can you explain how vaccinations protect us from infections?" They were then provided with three study documents, each of which was needed to solve the challenge. First, individual students from each group gathered to form twelve expert groups (four groups to study each expert material) and worked on their allocated materials over 1.5 lesson periods (each lasting 50 min.). Second, students returned to their original group (the *jigsaw* group) and shared and integrated their knowledge in order to solve the challenge problem. This jigsaw activity took another 1.5 lesson periods. The teacher was responsible for group composition in both group activities.

Study documents

We created the SBF framework for the human immune system based on a textbook description (Figure 1). We then discussed with the collaborating teacher the way to separate content, during expert group activities, into pieces of knowledge based on three essential functions: *humoral immunity*, *primary and secondary response*, and *cell-mediated immunity*. In the SBF framework, the three functions interact with one another as subsystems.

Study design

Pre- and post-tests

Students were questioned individually about their understanding of how the human immune system responds to vaccination (i.e., *Can you explain how vaccination protects us from infection?*). They were given a worksheet with a printed question, on which they could write or draw their ideas. The pre-test was conducted 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; their responses were then analyzed.

Process data collection

Student conversations during group activities were video-recorded and transcribed for vocabulary network analysis and ENA. We used transcripts of the jigsaw group activity to examine how students exerted their shared epistemic agency in advancing their collective knowledge.

Analytical procedure

With reference to the SBF framework for the human immune system, student explanatory discourse during the pre- and post-test was categorized into three types: (1) no understanding, (2) single-document understanding, or (3) integrated understanding. When students did not manifest any conceptual understanding of the three documents used in the expert group activity, they were categorized as having no understanding. Students who appropriately demonstrated understanding of one of the three documents were categorized as having single-document understanding. Those who manifested a more complete understanding of the human immune system, based on more than two documents in the expert group activity, were categorized as having integrated understanding. The first and third authors independently evaluated ten randomly selected examples of student discourse 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 all students were categorized as having no understanding in the pre-test, we focused on levels of understanding in the post-test to assess learning outcomes.

To visualize and computationally investigate collective knowledge advancement, Oshima et al. (2017) selected 23 nouns to represent the structures and functions of the human immune system in the SBF framework. On average, students engaged in discourse exchange 358.5 times in the jigsaw groups (SD = 211.8). The socio-semantic network of vocabulary refers to meaningful links (i.e., co-occurrence) between words in exchanges. We then used an application called KBDeX (http://www.kbdex.net) to calculate the transition of the total value of degree centralities of nodes in the network across discourse exchanges, following the method used in previous research (Oshima et al., 2012). We then calculated the *term frequencies* (TF) of the selected vocabulary words, using the formula, $\mathrm{tf}(t, d) = 1 + \log(f_{t,d})$. We compared TF means across the groups to test whether the amount of discourse related to the human immune system differed significantly (particularly between high and low learning-outcome groups).

We conducted an ENA of the twelve groups' discourse, using the seven epistemic actions of shared epistemic agency (Damşa et al., 2010) to code each discourse exchange. Cohen's Kappa coefficients for the agreement between the two raters ranged between 0.47 and 1.00. Disagreements were resolved through discussion. Since we were interested in detecting the epistemic frames of shared epistemic agency exerted by all of the groups in relation to their learning outcomes, we conducted separate ENAs for high and low learning-outcome groups.

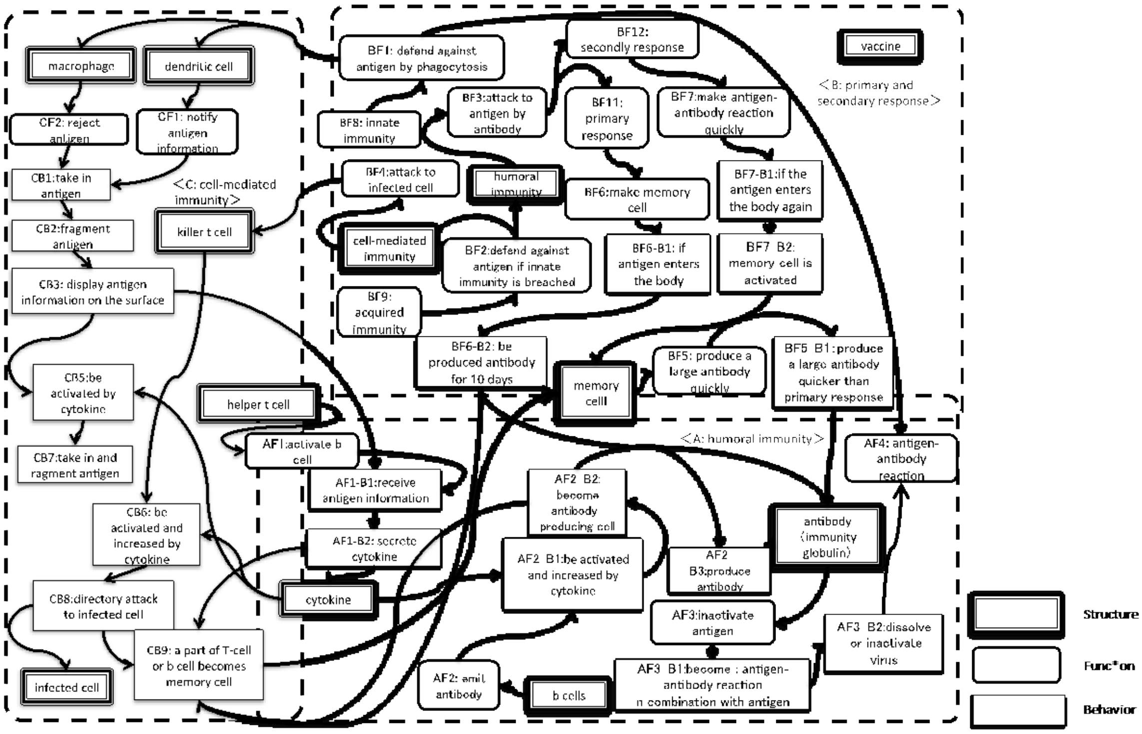


Figure 1. Structure–behavior–function framework of the human immune system.

Results

Students' learning outcomes at the individual and group level (Oshima et al., 2017)

We found that twenty-one students integrated SBF understanding. Eleven students demonstrated an understanding of a single part of a learned document; three did not sufficiently learn any piece of the SBF framework. A chi-square analysis of student frequencies across three types of learning outcome showed significance ($\chi^2 = 13.944$, $df = 2$, $p < .05$); in addition, the proportion of students who integrated SBF understanding was higher than the proportion with no understanding. These results suggest that the jigsaw activity did facilitate student integration of knowledge through collaboration, although group differences remained in the learning outcomes. Based on the SBF evaluation, we identified three high learning-outcome groups in which all members acquired integrated conceptual understanding. Nine low learning-outcome groups demonstrated mixed levels of understanding.

Collective knowledge advancement: the difference between high and low learning-outcome groups

Figure 2 shows the transitions in total values of degree centralities, an index presented in our previous study (Oshima et al., 2017) to detect collective knowledge advancement. We found that the values quickly increased and ultimately exceeded 10.0 in the high learning-outcome groups, while values stayed low and increased slowly across discourse exchanges in the low learning-outcome groups. These results suggest that students in the high-outcome groups engage in collective knowledge advancement more quickly and sustainably.

An additional one-way ANOVA of TFs found no significance among the twelve groups, $F(11, 198) = 2.35$, $p > .05$. This result reveals that students in all groups engaged in an equal amount of discourse related to the human immune system.

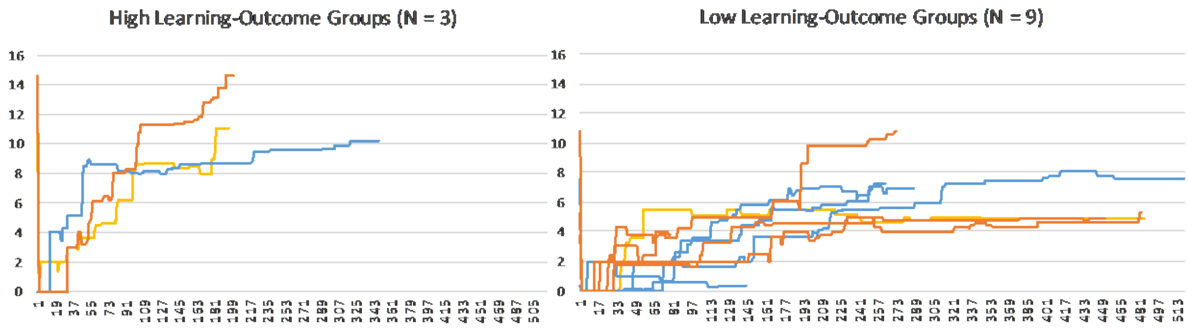


Figure 2. Transitions of total values of degree centralities over discourse exchanges.

Epistemic frames of shared epistemic agency: the differences between high and low learning-outcome groups

To examine epistemic frames of shared epistemic agency, we conducted an ENA of the discourse of students in high and low learning-outcome groups, using epistemic action codes (Figure 3). Seven codes of shared epistemic agency were plotted in a two-dimensional epistemic space, based on adjacency matrices representing the co-occurrence of the codes. A comparison of code connections in high and low learning-outcome groups revealed the following critical differences. First, we found differences in variances, explained by the two-dimensional epistemic spaces. For high learning-outcome groups, the epistemic space explained 100% of variances in the two-dimensional space (88.9% in the first/horizontal dimension and 11.1% in the second/vertical dimension). By contrast, for low learning-outcome groups, the epistemic space explained only 80% (46.3% in the first dimension and 33.7% in the second). In addition, the relationship between the epistemic and regulative aspects of actions differed in the two types of groups. In high learning-outcome groups, three epistemic actions—alleviating a lack of knowledge (ALoK), creating shared understanding (CSU), and generating collaborative actions (GCA)—were strongly linked to both regulative and projective actions. In low learning-outcome groups, although the three epistemic actions (ALoK, CSU, and GCA) were linked to regulative action, they were only weakly connected to projective action.

In addition to analyzing the differences associated with learning outcomes, we carried out a temporal analysis within each group, dividing the whole process of each group discourse into three phases (Figures 4 and 5). Based on the temporal ENA within each group, we found the following results. First, in high learning-outcome groups, the most active actions changed across the three phases, from ALoK through CSU toward GCA. In each phase, the active action was linked to regulative and projective actions. Low-learning outcome groups, by contrast, began with ALoK and continued to CSU but did not move further toward GCA. ALoK and CSU were linked to regulative action in the first and second phases; they were tied only weakly to projective action.

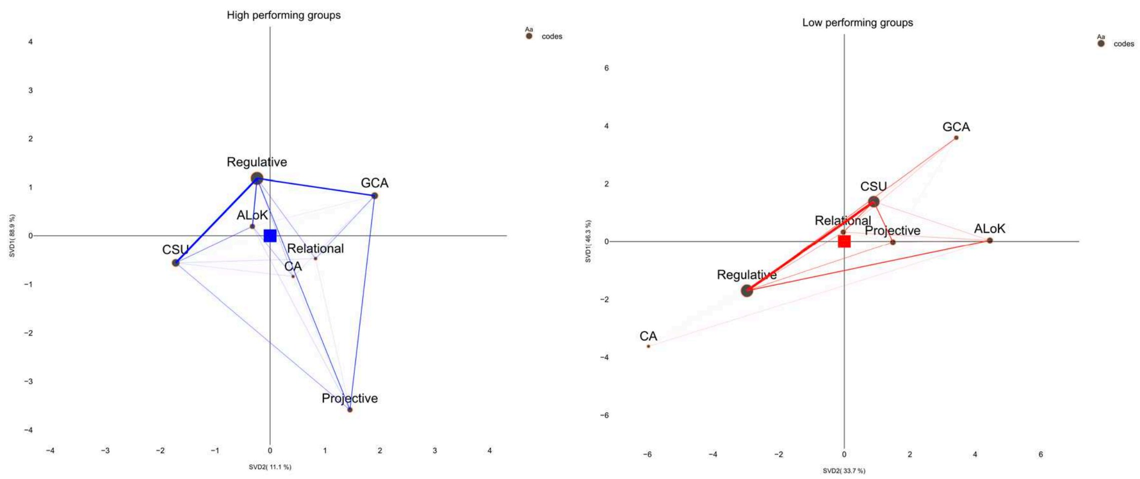


Figure 3. Epistemic frames based on seven epistemic actions in shared epistemic agency—
a comparison of high learning-outcome groups (left) and low learning-outcome groups (right).

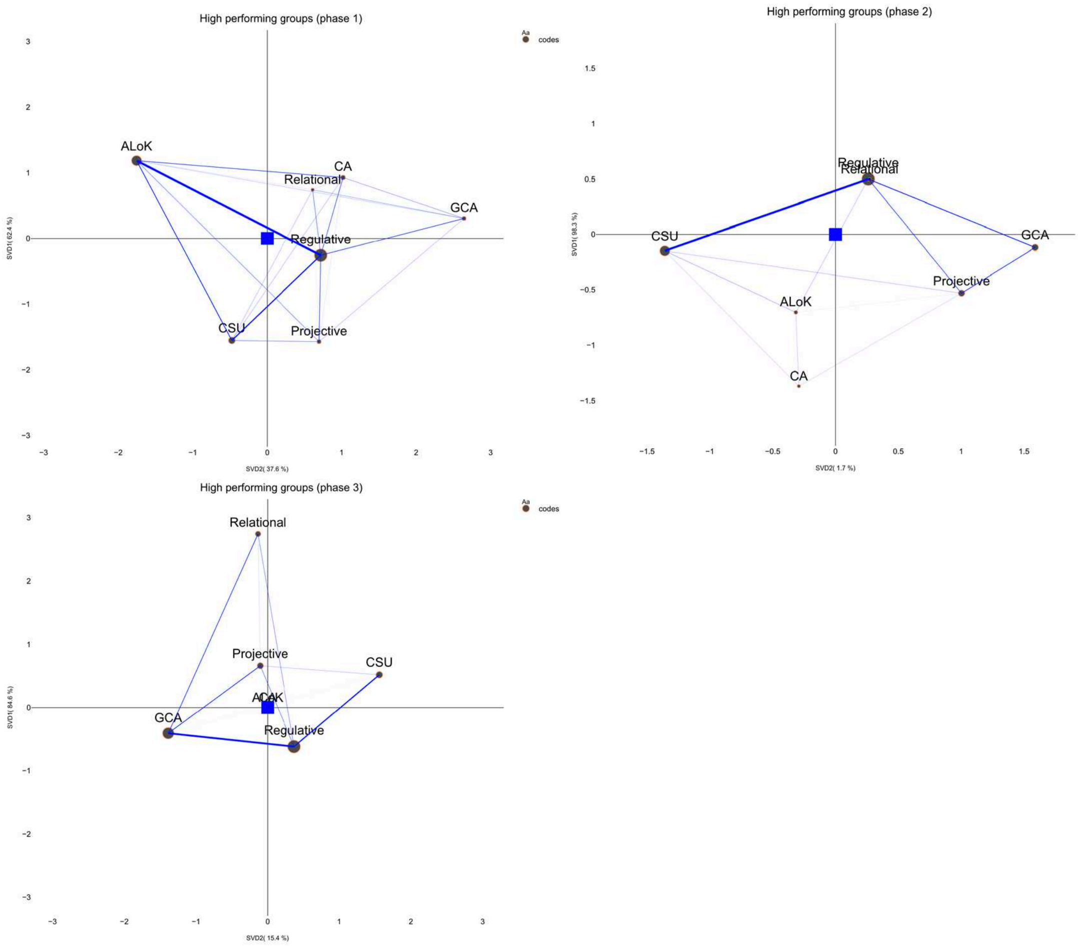
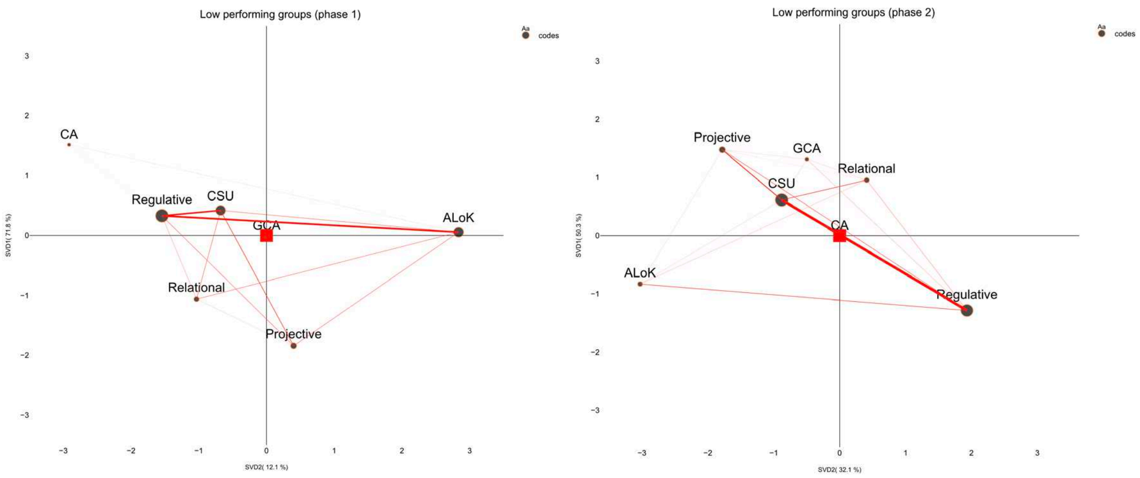


Figure 4. Temporal change in epistemic frames of shared epistemic agency by high learning-outcome groups: first phase (top left), second phase (top right) and third phase (bottom left).



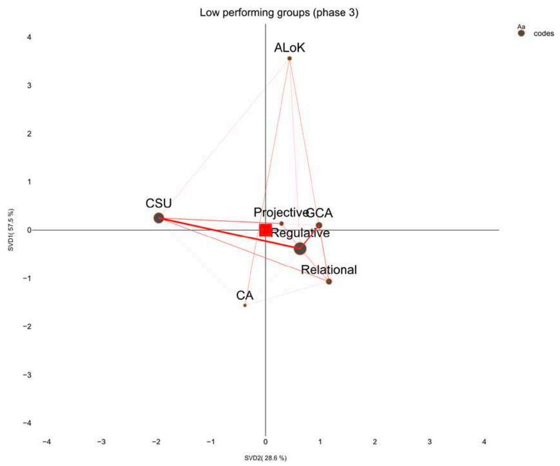


Figure 5. Temporal change in epistemic frames of shared epistemic agency by low learning-outcome groups: first phase (top left), second phase (top right), and third phase (bottom left).

Discussion

In our previous study, presented at CSCL2017, we looked only at how a jigsaw group activity improved students' ideas involving subject matter knowledge. Although significantly more students succeeded in acquiring integrated SBF understanding, we also found big differences in learning outcomes among student groups. Only three of the twelve groups (25%) succeeded in their collaboration, a problem that has now been examined more systematically using a double-layered socio-semantic network analysis. This approach has allowed us not only to analyze what happened in the jigsaw group activity (collective knowledge advancement) but also how it happened (shared epistemic agency). The new findings, mainly obtained through an ENA, led to the following interesting interpretations of the differences between high and low learning-outcome groups.

First, our additional analysis of vocabulary term frequencies related to the SBF framework for the human immune system revealed no significant difference in the amount of subject-related discourse across the groups. The fact that the amount of discussion was the same suggests that learning outcomes were not related to how much the students talked about the study topic. Instead, the way in which they scrutinized their own ideas appears to have been the key to more productive group-learning outcomes.

Second, our ENA of students' epistemic actions showed that the two types of groups (high and low) engaged in different types of epistemic agency. The high learning-outcome groups established more robust epistemic space (100% of explained variances) than the low learning-outcome groups (80% of explained variances). The most epistemic aspect of actions was linked to the regulative aspect of actions in the high learning-outcome groups. In addition to constructing a shared understanding, they also collaboratively generated actions based on their shared understanding to explain how vaccination protects us from infection. They took regulative and projective actions in relation to epistemic actions. In other words, they monitored their understanding and attempted to improve their ideas continuously, in order to create their own theories of the human immune system. No strong link between epistemic and regulative actions was found in the low learning-outcome groups.

Finally, our temporal ENA of the students' epistemic agency provided a more accurate understanding of the way in which they engaged in shared epistemic agency to advance collective knowledge. The high learning-outcome groups were more engaged in alleviating their lack of knowledge during the first phase of activity—before they constructed a shared understanding. By contrast, the low learning-outcome groups engaged in two types of epistemic actions simultaneously, starting in the first phase. During the third phase, they continued to construct a shared understanding and did not take the next step toward generating collaborative actions (for example, by creating new collaborative ideas). These results suggest that there may be an optimal sequence of epistemic actions, such as alleviating a lack of knowledge before constructing a shared understanding. The high learning-outcome groups appeared to monitor themselves and proceed in accordance with a sequential process.

By analyzing learning outcomes, collective knowledge advancement, and shared epistemic agency, we were able to see how students engaged in collective knowledge advancement through their shared epistemic agency when successfully acquiring a deep conceptual understanding. As previous research (e.g., Damşa, 2014; Scardamalia, 2002) suggests, epistemic agency plays a key role in successful collaboration. The present study introduces a new finding: epistemic actions in collective knowledge advancement are likely to follow a sequential process. This hypothesis should be further tested in future studies, which could incorporate design elements into jigsaw instruction to help students become aware of the sequence.

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Acknowledgments

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