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Knowledge convergence and collaborative learning

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Abstract. This paper operationalized the notion of knowledge convergence and assessed quantitatively how much knowledge convergence occurred during collaborative learning. Knowledge convergence was defined as an increase in common knowledge where common knowledge referred to the knowledge that all collaborating partners had. Twenty pairs of college students collaborated to learn a science text about the human circulatory system. Comparisons of individual pre-test and post-test performance revealed that students shared more knowledge pieces and mental models after collaboration. Although the amount of convergence was modest, analyses showed that collaborative interaction was responsible for the increase in common knowledge. The increase in common knowledge was observed in knowledge that was never stated in the learning text as well as in knowledge that was explicitly presented in the text. The amount of convergence was related to interaction such that real pairs shared more knowledge than nominal pairs, and more interactive pairs shared more inferred knowledge than less interactive pairs. Collaborative dialogues and learning artifacts (e.g., drawings) also indicated that common knowledge was constructed during collaboration. Possible reasons for the discrepancy between the impression of strong convergence assumed in the literature and the results of this study are discussed along with the need to develop a more comprehensive understanding of the notion that includes its process, outcome, and sources of convergence.

Keywords: Collaborative learning, common knowledge, knowledge convergence, shared cognition, text comprehension

Introduction

Knowledge convergence is the process by which two or more people share mutual understanding through social interaction, and is believed to reflect the fundamentally social nature of the knowledge construction process (Brown & Campione, 1996; Hutchins, 1991, 1995; Ickes & Gonzales, 1996; Lave & Wenger, 1991; Resnick, Levine, & Teasley, 1991; Rogoff, 1998; Roschelle, 1992; Vygotsky, 1978; Webb &

Palinscar, 1996). The goal of this paper was to explore what knowledge convergence might mean by providing *one operational definition* of knowledge convergence in order to assess it *quantitatively* in the context of collaborative learning.

Knowledge convergence: does it really occur?

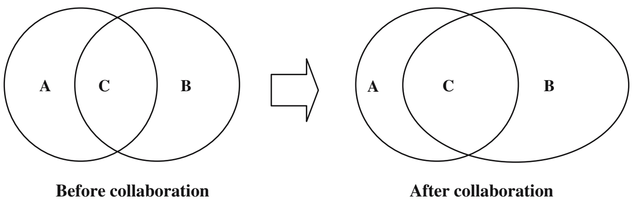
Knowledge convergence is one of the most basic and essential aspects of cognitive interdependencies among collaboration partners (Ickes & Gonzales, 1996; Roschelle, 1992). Convergence occurs because the reciprocal nature of collaboration leads to an increased similarity in the cognitive representations of the group members. Roschelle (1992) studied a pair of high school students as they collaborated to learn the concepts of velocity and acceleration in physics. Based on the analysis of students' exchanges, Roschelle (1992) concluded that the two students' representations converged during collaboration and proposed convergence to be the "crux" of collaboration. Although his work strongly claimed convergence as one of the key mechanisms of collaboration, not everyone agreed with his conclusion. Graesser, Person, and Magliano (1995) examined knowledge convergence in one-to-one tutoring situations. Although collaborative learning is different from tutoring, one can stipulate that similar convergence would occur in one-to-one tutoring situations such that the tutee's conception of the subject matter would converge toward that of the tutor's. Unlike Roschelle (1992), however, they reported that no convergence occurred between tutors and tutees during tutoring.

Although there are potentially a number of reasons for why existing studies reached different conclusions, one important reason for the discrepancy is that it has been difficult to define the notion of knowledge convergence in a precise manner. In the past, researchers relied on an intuitive definition of knowledge convergence and have undertaken mostly qualitative analyses to understand the concept (e.g., Azmitia, 1988; Forman & Cazden, 1985; Hutchins, 1995; Graesser, 1995; Roschelle, 1992; Teasley & Roschelle, 1993). In this paper, we offer a cognitive and quantitative definition of knowledge convergence to complement the mostly qualitative analyses that have been undertaken so far. Although our operational definition may be simplistic, it offers a means to accurately assess how much convergence is achieved during collaboration.

A definition of common knowledge and knowledge convergence

Suppose that there is a pair of participants consisting of Ann and Bob. We can schematically depict the relationship between their knowledge representations as in Figure 1. In Figure 1, what each individual knows is represented as a circle: the one on the left represents what Ann knows (Knowledge A & C), and the one on the right represents what Bob knows (Knowledge B & C). Some of their knowledge is held in common (Knowledge C), whereas other knowledge is unique to each person (Knowledge A for Ann & Knowledge B for Bob). We define common knowledge to be the knowledge that all participants know (Knowledge C), that is, the overlaps of individual knowledge representations. Based on this notion of common knowledge, we define knowledge convergence to be an increase in common knowledge following collaboration. If the amount of common knowledge increases after collaboration, knowledge convergence is said to occur.

Note that there are several different outcomes of collaborative interaction and the notion of shared or joint understanding has been defined in a variety of ways. Thompson and Fine (1999) pointed out that there exist at least three different meanings of "socially shared meaning," such as (a) *divided up into portions* as in distributed cognition (e.g., Hutchins, 1995) and transactive memory (e.g., Wegner, 1987); (b) *held in common* as in team mental models (e.g., Cannon-Bowers, Salas, & Converse, 1993) and group mind (e.g., Bar-Tal, 1990); (c) *partaking in agreement*, relating to the notion of consensus and agreement as in intersubjectivity and common ground (e.g., Clark & Brennan, 1991). Although they are all about how groups share



Measures	Areas in Figure 1
What Ann knows	A + C
What Bob knows	B + C
Common KPs	C
Unique KPs	A, B
Distinct Total KPs	(A+B+C)

Figure 1. Common knowledge, Unique knowledge, and Distinct Total knowledge.

knowledge and cognitive processes, they differ in important ways. The first category of meaning, *divided up into portions*, focuses on what is differentiated or divided in group members' representations, often developed as a result of adopting different roles. The second category, *held in common*, focuses on what is same or common in group members' representations or knowledge base. The last category, *partaking in agreement*, focuses on what is agreed among group members.

Our definition of common knowledge refers to the overlap in participants' representations and most closely resembles the second category, *held in common*, in Thompson and Fine's (1999) categorization. It assesses one of the several outcomes of collaborative interaction. In this respect, note that our notion of common knowledge is distinct from the notion of "common ground" or "mutual knowledge" proposed by Clark and his colleagues (e.g., Clark, 1996; Clark & Wilkes-Gibbs, 1986). When a contribution is made in a dialogue, it needs to be grounded so that the speaker and/or the listener make sure that their partner understands their contribution and/or they understand their partner's contribution. During a conversation, participants actively seek evidence of grounding by asking questions or requesting repairs (e.g., "did you mean this?") or provide evidence of grounding by acknowledgement or with continued attention. A contribution, once grounded, becomes a part of the "common ground" or mutual knowledge, which refers to the knowledge that "Person A knows that Person B knows X." Common ground is about an awareness of what conversational partners know. As such, common knowledge and common ground refer to different outcomes of collaborative interaction. Common knowledge refer to the similarities in representations itself, whereas common ground refers to the awareness of the similarities, that is, the awareness of what is shared among conversational participants. In addition, when a listener grounds a contribution by paying attention to the speaker or acknowledging a contribution, he or she often does not encode and process the contribution to a sufficient degree so that it would become part of his or her representation. This means that even when a contribution is grounded and becomes part of the common ground, it does not necessarily become a part of the participants' representation and/or common knowledge. By assessing what individuals know, common knowledge provides a stricter and more conservative estimate of what is held in common.

Different origins of knowledge convergence

Researchers from anthropology and organizational science have reported that various kinds of groups that have histories of interaction tend to share a set of common knowledge. For example, Orr (1990) reported that people who practice the same job (e.g., photocopier repair technicians) hold a "community memory" that all or most members of the community know about their machines and customers. Similarly, teams are reported to have a team mental model about task requirements, procedures, and responsibilities (Cannon-Bowers et al., 1993; Klimoski & Mohammed, 1994; see also Hazlehurst, 1994). Researchers have assumed that such shared knowledge emerged as a result of group interaction. During collaborative interaction, people jointly interpret a situation, coordinate their understanding, and come up with a solution to a problem together. As a result of such joint construction activities, similarities in their representations were seen to arise. However, the existence of community memory or a team mental model does not necessarily mean that these were constructed through collaboration. Members of a group or a culture are constantly exposed to a set of shared input such as news media or books. It is equally likely that convergence occurred because group members all received the same input and experienced the same events.

In general, we can distinguish two different sources of knowledge convergence. First, group members could have the same or similar knowledge because their members experienced the same environmental and cultural conditions. Second, group members could have the same or similar knowledge because members collaboratively interpreted a situation or solved a problem together. Existing studies seldom distinguished between these two different sources of convergence, with the possible exception of Sherif (1936). By selecting a task that minimized the influence of shared input, he demonstrated how interaction alone could lead to convergence. When a fixed light is presented in a completely dark room, the light appears to move erratically. This phenomenon is known as auto-kinetic movement. In his experiment, participants were placed in the dark and were asked to estimate how much the light appeared to move. When participants performed the task alone, each individual established one's own frame of reference to estimate the movement of the light source, which was quite different from that of other participants. However, when they performed the task in groups of two or three people, they quickly established the same frame of reference, even though their initial frame of reference was quite different from one another's. Participants all received the same input regardless of whether they worked in groups or alone, but agreement occurred only when they worked in groups and shared the experience of estimating the light movement together.

In Sherif's (1936) study, the nature of the input was such that its influence was kept to a minimum. In a typical collaborative situation, however, it is difficult to control the influence of the input to such an extent. Group members not only share a host of inputs, including task environment, but also interact over them. It is neither possible nor desirable to control the shared input completely since it would make the situation too artificial and would limit the kinds of collaboration we could study. However, even though it is difficult to separate the two different origins of convergence, it is important that researchers are aware of the different sources of convergence and evaluate their relative contributions appropriately.

Present study

The main research question of this study can be stated as the following: Does collaboration lead to an increase in common knowledge? If so, can the source be specifically attributed to collaboration? In order to answer these questions, we first assessed the increase in common knowledge using the definition we outlined earlier. In line with Roschelle (1992), we expected that the amount of common knowledge would increase, that is, students' knowledge representations would become more similar to each others' after collaboration.

Second, we explored whether and how much of the obtained convergence is attributable to collaboration. As discussed earlier, it is difficult to separate the differential contribution of interaction and learning materials in a situation such as in this study because students share a learning material as well as interact over it. However, we attempted to identify the independent contribution of collaborative interaction as much as possible. The following four specific questions guided our exploration.

1. Was knowledge convergence a by-product of learning? As students collaborate, the amount of knowledge (i.e., the overall size of the individual circles in Figure 1) would increase as well. Thus, the increase in common knowledge might be a by-product of learning, rather than the result of collaboration.
2. Did knowledge convergence occur in knowledge that was not explicitly stated in the learning materials as well? If students

constructed common knowledge solely based on the shared text, they would be less likely to construct common knowledge if it was not explicitly stated in the text.

3. Did knowledge convergence vary as a function of interaction? To the extent that collaboration was responsible for knowledge convergence, the amount of convergence would vary as a function of collaboration. More convergence would occur with one's own partner than with someone else's partner. In addition, the more they collaborated, the more convergence would occur.
4. Did knowledge convergence originate from specific collaborative episodes? Not all common knowledge would result from collaborative interaction. However, to the extent that collaborative interaction was responsible for common knowledge construction and to the extent that dialogues capture joint construction activities, we should be able to find evidence of common knowledge construction from collaborative learning episodes.

In this study, college students were asked to collaborate to learn a science text about the human circulatory system. The collaboration was unstructured in order to obtain a base line measure of knowledge convergence in naturalistic collaborative learning situations. No specific instructions were given except for the instruction to collaborate and to talk. No time limit was imposed either so that their collaboration would not be biased or compromised. Students were tested individually before and after the collaborative learning session. Although the majority of the studies that investigated collaborative learning used problem solving tasks, collaborative text comprehension is not *un*common in real life (e.g., this is what we do in a seminar) and has been successfully used as a collaboration task by other researchers (e.g., Brown & Palincsar, 1989; or Chan, Burtis, & Bereiter, 1997). The text used in Chi, de Leeuw, Chiu, and LaVancher (1994) was used with a slight revision in this study. The use of this material allowed us to undertake a detailed assessment of students' knowledge, which was important to determine the degree of convergence in students' representations in this study.

Method

Participants

Twenty (nine male and 11 female) pairs of undergraduate students enrolled in introductory psychology classes at the University of

Pittsburgh participated in the study for course credit. The average age of the participants was 20 years old. The mean of their GPAs (Grade Point Average) was 2.80.

Students were asked to participate if they had not previously taken any college-level biology classes prior to the participation in the study. Students were asked to stay in the study if they had *inaccurate* models of the human circulatory system at the pre-tests (neither Double Loop-1 nor Double Loop-2; see later coding section for details about the models) and did not have relevant personal experiences.[1]

Pairs were formed randomly as long as they were of the same gender and race and were available at the same time.[2] None, except for one pair, had interacted with their partner prior to the study.

Nominal pairs

This study did not have an actual control group, but used nominal pairs as a control instead. Nominal pairs were constructed *post hoc* by randomly pairing two students who had not worked together (see Figure 2). See the results section for how they were used in the analysis.

Materials

Text

The text used in Chi et al. (1994), originally taken from the chapter on the human circulatory system in a high school biology text by Towle (1989), was used with a slight revision. The revision involved deleting parts of the text that were not directly relevant to the human circulatory system (e.g., diffusion). The resulting text contained 73

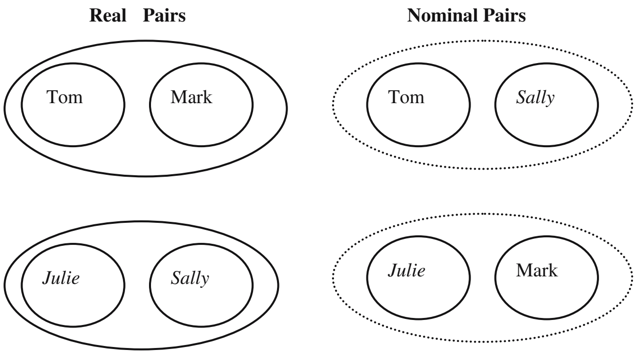


Figure 2. The construction of nominal pairs. The names of the first pair are in plain text, whereas the names of the second pair are in italics. Real pairs are grouped with a solid line, whereas nominal pairs are grouped with a dotted line.

sentences. Each sentence was printed on a separate page and presented in a three-ring binder.

Terms task

This task consisted of 19 key terms about the human circulatory system (e.g., atrium, ventricle). Students were asked to talk about everything they knew about each term, one by one, even if it seemed unimportant to them. This task can be considered a free-recall or cued-recall task that assesses their knowledge about the circulatory system.

Blood path drawing task

The task consisted of color pens and a sheet of paper that contained an outline of a human body with a heart in it. They were asked to draw the blood path of the circulatory system in the outline and to talk about everything that came to mind as they drew.

Knowledge questions

A set of knowledge questions was used to assess students' understanding of the circulatory system in depth. There were five different kinds of questions. *Category 1 Questions*, also called "verbatim" questions, were designed to test the knowledge that can be directly obtained from the text. For example, question (1-16) "Why are there valves in the heart?" can be answered directly from Sentence 23: "One-way valves separate these chambers and prevent blood from moving in the wrong direction." *Category 2 Questions* were designed to capture the kind of knowledge that can be learned by connecting different pieces of information explicitly stated in the text. To answer these questions, students needed to connect information that was explicitly presented in the text, often in different parts. *Category 3 Questions* were inferential questions designed to capture new knowledge generated based either on the text or on their prior knowledge. Answering these questions required a good deal of understanding of the text and the use of prior knowledge (e.g., domain-relevant or common sense knowledge). *Health Questions* were application questions designed to assess students' understanding of the implications of the system-wide properties of the circulatory system. Answering them required application of their knowledge to various health problems. There were 10 questions for each question type.[3] See Chi et al. (1994) for a detailed description of how the questions were constructed.

Procedures

Pre-test

Participants were tested individually on the Terms Task and the Blood Path Drawing Task. The pre-test session took about 15–30 minutes and was audio-taped. At the end of the session, participants were asked not to do outside reading on this topic while the study was in progress.

Collaborative learning

About a week after the pre-test, students came back to study the text with a partner. Since most of them had never met each other, they were allowed some time to get to know each other before the session started. When the two students arrived at the lab, the experimenter introduced them and initiated a conversation (e.g., Who is your psychology instructor?). She then left the room supposedly to check on the equipment. The experimenter watched their interaction from a monitor in another room until they seemed to be comfortable with each other. Most students quickly established a rapport with each other, discovering a common friend or exchanging information about classes. This process took about 10 minutes. Once learning began, the experimenter was not present in the room except to give instructions and to exchange tapes. However, the experimenter could hear and watch the students from another room. Students knew that the experimenter could hear but not necessarily watch them and that they could ask questions to the experimenter if they wanted to.

Students were instructed to collaborate to learn the text. They were to talk and to help each other in learning the materials, but no other specific instructions about how they should collaborate was given (see Appendix for the instructions). The pairs shared the text binder and were asked to read out the text aloud at least once. They knew that they would be tested later. A few sample test questions were provided. They were allowed to take as much time as they needed to study the text. The actual collaborative learning session took about an hour on average, ranging from 40 minutes to 1 hour and 45 minutes. This session was audio- and video-taped.

Post-test

A post-test was carried out about a week after the collaborative learning session. A week-long delay was introduced in order to assess a robust, long-term change in their knowledge representation, instead of assessing an immediate recall of their working memory contents right after the learning session. Students were tested individually on the Terms Task, Blood Path Drawing Task, and Knowledge Questions. Students' answers were all audio-taped. The session took from 45 minutes to 2 hours. After they finished, they were interviewed about the collaborative learning session and asked for permission to release their GPAs.

Coding & reliability

All the tapes were transcribed. From the transcribed data, we coded the following measures as described below. For reliability, a second coder coded 20% of the data independently. Specific reliability measures are reported with each coding explanation. In order to preserve consistency in coding, the coding of the first coder was used throughout.

Template scoring

A template was created to assess how much students knew about the various terms and concepts covered in the learning text. It was coded using the students' protocol during the Terms Task and the Blood Path Drawing task of the pre-test and post-test. The template consisted of individual Knowledge Pieces (KPs) that roughly corresponded to a proposition (e.g., aorta is an artery). There were two types of KPs: Stated KPs and Inferred KPs. Stated KPs referred to the KPs explicitly stated in the text and were identified by segmenting and collapsing the 73 sentences into individual knowledge pieces. An example of a Stated KP was "the atrium is the upper part of the heart" which was directly stated in Sentence 20: "Each upper chamber is called an atrium." Inferred KPs referred to the knowledge that needed to be inferred from the text. An example of an Inferred KP was "the heart has four chambers." This KP was not explicitly stated in the text but could be inferred by integrating Sentence 17: "The septum divides the heart lengthwise into two sides" and Sentence 19: "Each side of the heart is divided into an upper and a lower chamber." Note that there could be an unlimited amount of inferred knowledge, but we only included knowledge that can be easily constructed with minimal inference and the domain knowledge necessary to understand the materials (e.g., there are two lungs). The template contained 173 KPs in total, among which 115 KPs were Stated KPs and 58 KPs were Inferred KPs. Students were given a point for each KP that they stated or drew. The reliability between the two coders' scores was $r = .94$.

Incorrect knowledge pieces

Template coding captured only the correct knowledge discussed in the text. We coded incorrect knowledge from students' answers to the Terms Task and the Blood Path Drawing Task. We focused on the incorrect conceptual knowledge that was about the structural or functional aspect of the circulatory system (e.g., "the heart oxygenates blood"). Because there were very few cases of such errors (see the Results section), no reliability check was done for this coding.

Mental model analysis

Students' initial and final mental models about the human circulatory system were coded to assess changes in how individual knowledge was integrated to form a coherent model of the circulatory system as a whole. Based on students' answers during the Terms and the Blood Path Drawing tasks, their initial mental models at the pre-test and final mental models at the post-test were coded into one of the seven models. These seven models are (1) No Loop (NL) model, (2) Ebb and Flow (EF) model, (3) Single Loop (SL) model, (4) Multiple Loop (ML) model, (5) Single Loop with Lungs (SLL) model, (6) Double Loop-1 (DL1) model, and (7) Double Loop-2 (DL2) model (see Figure 3). The models differ from each other in terms of the kinds of incorrect conception (e.g., blood returns to the heart by way of the same blood vessels) and/or the correct conceptions (e.g., knowing merely that the heart pumps blood to the lungs versus knowing that the left ventricle of the heart pumps blood to the lungs). Both the Double Loop-1 and Double Loop-2 models represent the accurate flow of blood through the circulatory system, although the latter was the most complete model (see Chi et al., 1994 for more details on this analysis). The inter-rater agreement on mental model coding was 94% and Cohen's kappa was .92.

Knowledge questions

Each of the Category 1–3 and Health questions received a maximum of five points. The inter-rater reliability was $r = .98$ for the Category 1 Questions, .81 for the Category 2 Questions, .77 for the Category 3 questions, and .84 for the Health Questions.

Turn-taking

We coded students' turn-taking behavior in order to determine the amount of interaction students engaged in during collaborative learning. We first identified turns in the learning dialogue. The transcript occasionally contained non-verbal (e.g., laughs, gestures) turns. A

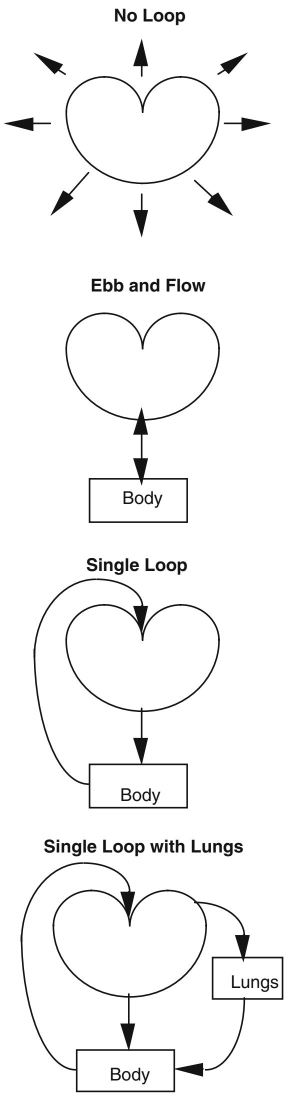


Figure 3. The seven mental models about the human circulatory system.

non-verbal turn was coded as a separate turn if it was communicative (e.g., nodding, indicating "yes"). Similarly, turns that contained only "ok" or "umm" were coded as a separate turn when it could be an answer or acknowledgement. Based on this turn identification, each turn was coded whether or not it was relevant to their partner's previous turn. A turn was coded as relevant if it contained information relevant to their partner's previous contribution in some way. For example, a turn was deemed relevant if students (a) asked or answered questions that their partner asked, (b) repeated and/or continued the statement or the topic that their partner initiated, or (c) acknowledged what their partner said in that turn. The correlation between the two coders' relevancy judgment scores was $r = .99$.

Results

Learning

Students' learning was analyzed in two ways. First, we examined the amount of individual KPs students knew. The average amount of KPs that each member of the pairs knew increased significantly after collaboration from 19.70 KPs to 47.70 KPs, $t(19) = 10.08$, $p < .001$. Second, we analyzed students' mental models. Consistent with the overall gain in KPs, students' individual mental models about the circulatory system improved as well. Since only students with incorrect models participated in the study, none had the correct Double Loop-1 or Double Loop-2 models at the pre-test: the majority had the Single Loop model (55%), followed by the Single Loop with Lungs model (25%), No Loop model (17.5%), and Ebb and Flow model (2.5%). After learning, however, the majority of the students possessed the most accurate and complete Double Loop-2 model (52.5%), followed by the next accurate Double Loop-1 model (37.5%), and Single Loop model (10%). Learning the text with a partner increased the number of individual knowledge pieces that they knew and also improved the accuracy of the students' mental model, as was reported in Chi et al. (1994).

Common knowledge

In line with the analyses of learning, knowledge convergence was also analyzed in two ways. First, we examined the convergence in individual KPs. As defined earlier, knowledge convergence was defined as an increase in common KPs where common knowledge referred to the knowledge that both partners knew. If both partners knew a particular KP (e.g., the heart has four chambers), then that KP was coded as a Common KP. If that KP was not common at the pre-test, but became common at the post-test, it was said that knowledge convergence occurred for that particular piece of knowledge. The amount of

Common KPs increased significantly after collaboration from 7.25 KPs to 22.55 KPs, $t(19) = 6.13$, $p < .001$.

Second, we compared each student's mental model with their partner's. At the pre-test, 10 pairs held common mental models and 10 did not. Although the 10 pairs who shared the initial model did so by way of coincidence, to get a stricter picture of convergence, we examined the convergence in these two groups separately. As for the 10 pairs whose initial models were *different*, six of them converged onto the same final model. As for the 10 pairs whose initial models were the *same*, five of them converged onto the same final model. Overall, about half of them (55%) converged on the same final model, and the amount of convergence was similar in the two groups.

Note that the amount of common knowledge was by no means extensive. Even when students started out with the same mental model and studied the same text, only about half of them ended up with the same model. In addition, even the modest amount of convergence could not be entirely attributed to collaboration. As described earlier, since students all learned the same text in this study, there was a possibility that the increase in common knowledge and the convergence toward the correct final model might be the result of learning the same materials. In the next section, we explored whether knowledge convergence obtained in this study could be attributed to collaboration.

Collaboration and knowledge convergence

Question 1: Was knowledge convergence a by-product of learning?

Although pairs had more common knowledge after collaborative learning, they also knew more. This means that the increase in common knowledge might have been due to the fact that students learned new knowledge during collaborative learning. In order to examine this possibility, we considered the amount of learning in evaluating the degree of common knowledge construction. We also examined whether common knowledge and the rest of the knowledge (i.e., unique knowledge) showed the same pattern of relationship with various learning measures.

(1) Percentage of change. To take into account the amount of learning, we examined whether the *percentage* of Common KPs increased after collaboration. In calculating the percentage, we used the Distinct Total KPs ($A+B+C$ in Figure 1's notation) as a base. It makes more sense to use the Distinct Total KPs as the denominator because an arithmetic calculation of total knowledge would include

common knowledge twice ((A + C) + (B + C)), whereas the Distinct Total KPs includes it only once, capturing the total amount of unique knowledge available to the pairs more accurately. The percentage of Common KPs increased after collaboration from 23% to 30%, $t(19) = 2.8$, $p < .01$ (see Figure 4), indicating that the increase in the common knowledge was more than the increase in the distinct total knowledge.

(2) Correlations with learning outcomes. We examined how the strength of association between the common/unique knowledge and the distinct total knowledge changed before and after collaboration. The correlation between Unique KPs and Distinct Total KPs became significantly weaker after collaboration, from $r = .95$ to .83, $z(17) = 1.88$, $p < .05$. On the other hand, although not significant, the correlation between Common KPs and Distinct Total KPs became stronger after collaboration, from $r = .68$ to .82.

We also examined the correlations between the common knowledge and the post-test knowledge questions. Partial correlations were computed with pre-test scores as a control (i.e., pre-test Common KPs and pre-test Distinct Total KPs) (see Table 1). In general, the amount of common knowledge was significantly correlated with

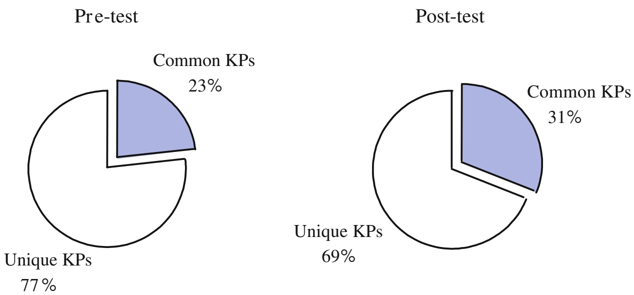


Figure 4. Changes in Common and Unique KPs in real pairs.

Table 1. Partial Correlations of Common and Unique KPs with Knowledge Questions

	Common KPs	Unique KPs
Category 1 Questions	.26	.44[a]
Category 2 Questions	.62*	.21
Category 3 Questions	.54*	.13
Health Questions	.63*	.27

*$p < .01$.
[a]$p < .07$.

students' post-test scores in all the Knowledge Questions except for the Category 1 Questions. However, unique knowledge was not significantly correlated with any of the questions. It was only marginally correlated with the Category 1 Question. After collaboration, the common knowledge became more strongly associated with the pairs' overall performance than the unique knowledge and characterized the pair's total knowledge better. In addition, recall that Category 1 questions are called "verbatim" questions because answers to these questions were directly stated in the text. The differential correlation pattern of Category 1 from the rest of the knowledge questions suggests that acquisition of verbatim knowledge may be less dependent on interaction, but rather on some other factors such as individual students' prior knowledge or learning skills.

Question 2: Did knowledge convergence occur in knowledge that was not explicitly stated in the learning materials as well?

Although receiving the same information does not necessarily lead to the formation of an identical representation, it would certainly increase the likelihood that people would come up with the same or similar representation as compared to not receiving the same input. When pairs shared a piece of knowledge that was explicitly given in the learning text, it would be more likely that they constructed it independently from the text. Although sharing a knowledge piece that was *not* stated in the learning materials does not necessarily mean that it is jointly constructed, when pairs shared such knowledge it would be more likely that they constructed it during collaboration. In this section, we examined whether knowledge convergence occurred with respect to the knowledge that was not explicitly stated in the text. We did it with two categories of knowledge, inferred knowledge and incorrect knowledge.

(1) Inferred Common Knowledge. As reported earlier, pairs shared 7.25 KPs at the pre-test, which increased to 22.55 KPs at the post-test. Among the 7.25 Common KPs that pairs shared at the pre-test, 5.85 KPs were Stated KPs and 1.40 KPs were Inferred KPs. Among the 22.55 KPs that the pairs shared at the post-test, 19.15 KPs were Stated KPs and 3.40 KPs were Inferred KPs. Since the template contained more Stated KPs than Inferred KPs (115 versus 58), we examined the percentage of Stated KPs and Inferred KPs. Common knowledge increased significantly both in Stated and Inferred KPs after collaboration. Common Stated KPs increased from 5% to 17%, $t(19) = 6.12$, $p < .001$ and Common Inferred KPs increased from 2%

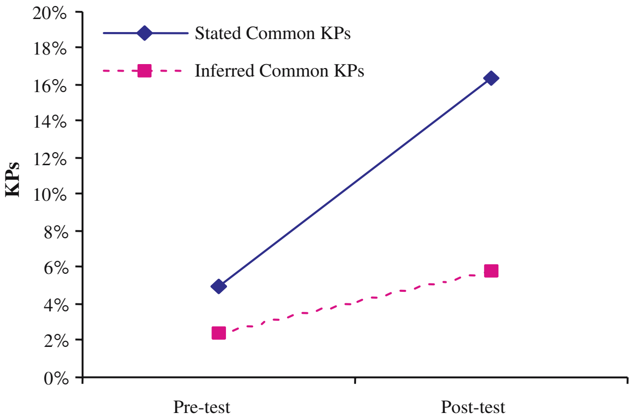


Figure 5. The increase in Stated Common KPs and Inferred Common KPs.

to 6%, $t(19) = 4.02$, $p < .001$ (see Figure 5). Although the increase in inferred knowledge was modest, common knowledge was constructed in knowledge that needs to be inferred from the text as well.

(2) Incorrect Common Knowledge. The pairs did not share any incorrect structural or functional knowledge at the pre-test, but there were four cases in which they shared incorrect knowledge pieces at the post-test. They were (a) there is a valve when blood enters the heart, (b) blood flows from left ventricle to left atrium, (c) diffusion occurs in the heart, and (d) arteries have valves. As for the mental model, four pairs shared models other than the Double Loop-2 model at the post-test as described earlier. Among them, in one of the pairs who shared Double Loop-1, it was not a typical Double Loop-1 model. Students were typically coded to have Double Loop-1 when their model lacked the specific details of Double Loop-2 (e.g., exact location of where the blood enters the heart). But the students were categorized to have Double Loop-1 in this case because their models contained an incorrect detail. Both members of this pair thought that blood flowed from ventricle to atrium (this error was also captured in the incorrect knowledge pieces analysis reported above). The correct understanding was that blood from the lungs went to the heart through the *atrium* on the left side of the heart. However, both members of this pair believed that blood from the lungs goes back to the heart through the *ventricle* on the left and then to the left atrium (see Figure 6). Although sharing incorrect knowledge and mental model could also be a coincidence, sharing such a specifically flawed model and knowledge strongly suggests that it was jointly constructed through collaborative interaction.

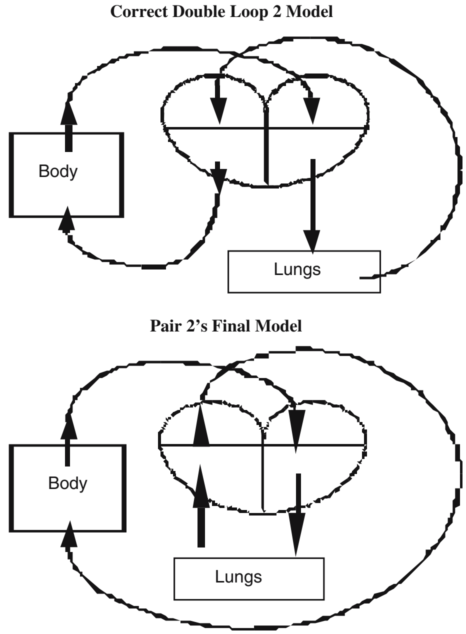


Figure 6. Double Loop-2 model and Pair 2's incorrect model.

Question 3: Did the amount of knowledge convergence vary as a function of interaction?

As we mentioned earlier, if convergence resulted from collaboration, the amount of convergence should vary as a function of collaboration. We examined this question in two ways. First, we compared the performance of real pairs against the performance of nominal pairs. Second, we compared the performance of more interactive pairs against the performance of less interactive pairs.

(1) Nominal Pair Analysis. If more convergence occurred in pairs who actually interacted, such a finding would indicate more strongly that common knowledge was constructed as a result of interacting with the specific partner. Common KPs increased after collaboration in nominal pairs (see Figure 7), but the increase was greater in real pairs than in nominal pairs (8% versus 4%). Although ANCOVA (controlling for their pre-test scores) did not reveal a significant difference between the two groups, $F(1,36) = 2.36$, $p < .14$, the increase was significant in real pairs, $t(19) = 2.8$, $p < .01$, but not in nominal pairs, $t(19) = 1.20$, $p > .10$.

(2) Common Knowledge as a Function of Interaction. When people collaborate, the amount of interaction differs from pair to pair. We

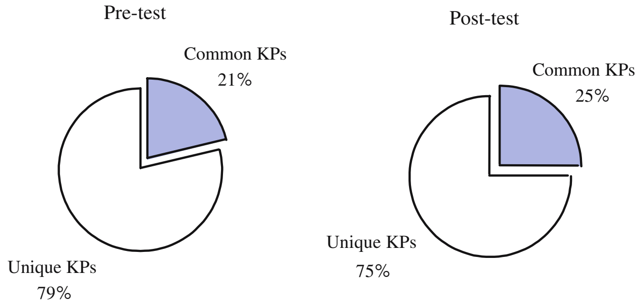


Figure 7. Changes in Common and Unique KPs in nominal pairs.

examined whether common knowledge construction varied as a function of interaction. If interactive pairs constructed more common knowledge, it would also mean that interaction was responsible for common knowledge construction. We used the percentage (to control for different amount of learning time) of relevant turns during collaborative learning as an index of interaction and formed two *post hoc* groups using median split: high-interaction pairs ($N = 10$) and low-interaction pairs ($N = 10$). The high-interaction group engaged in relevant turn-taking for 67% of the time, whereas the low-interaction group did so for 51% of the time. An ANCOVA (controlling for pre-test scores) compared whether the two groups differed in terms of the amount of common knowledge they constructed after learning. Although the high-interaction group constructed more common knowledge than the low-interaction group (26.9 KPs versus 18.2 KPs), the difference was not significant. The difference between the two groups became clear when the two groups were compared in terms of the types of knowledge they constructed. Two separate ANCOVAs (controlling for pre-test scores) revealed that high-interaction pairs shared significantly more inferred knowledge than low-interaction pairs after collaboration (4.5 KPs versus 2.3 KPs), $F(1,17) = 6.10$, $p < .05$, but not more stated knowledge, $F(1,17) = .11$, $p > .10$. More interaction led to more knowledge convergence, especially in inferred knowledge. In addition, the result that the effect of interaction was pronounced in inferred knowledge corroborated the finding reported in an earlier section that the effect of collaboration was on the construction of more elaborate, inferred knowledge than on the construction of explicit, factual knowledge.

Question 4: Did convergence originate from specific collaborative episodes?

In order to find out whether the common knowledge originated from collaborative interaction, we examined the four pairs who constructed incorrect knowledge. Although we were able to find episodes that can be linked to the construction of incorrect knowledge pieces in all four pairs, we present the data from two pairs where the evidence was more straightforward.

(1) *Case 1*. In one pair (Pair 2), the students incorrectly believed that blood from the lungs goes back to the heart through the left ventricle and then to the left atrium. We examined this pair's collaborative learning dialogue and found that the following exchange occurred when the text described the flow of blood from the lungs back to the heart (the text is highlighted, and our comments are in brackets).

(1) **L: 34) The** oxiden.. **oxygenated blood returns to the left atrium of the heart**.
(2) [Both look at the drawing]
(3) **M:** Ok, so.. Do you want to draw the red..
(4) **L:** Sure. How's it get up there?
(5) **M:** [showing the path of blood with her finger] through the right atrium [the motion of the finger is from ventricle to atrium]
(6) **L:** Oh, ok
(7) **M:** I think it goes like that
(8) **L:** [drawing] Ok
(9) **M:** So it goes back up through heart
(10) **L:** The.. it goes to the atrium then?
(11) **M:** [looking at the text and re-reading the text line] Returns to the left atrium of the heart
(12) **L:** So it's up here? [pointing the drawing]
(13) **M:** Right. So it must be moving through the vessels..
(14) **L:** [drawing] I'm going to just draw ..coming [laughing].. goes back
(15) **M:** Back into the atrium.. right?

As we can see from the exchange, after they read Sentence 34, Student L asked (in Turn 4) "how's it [the blood] get up there [left atrium of the heart]?" M gestured (in Turns 5 & 7) that it came from the *ventricle* (rather than from the lungs) and also added (in Turn 9) "it [blood] goes back *up* through the heart" (rather than *down* through the heart). It is not clear whether M had already constructed this piece of incorrect knowledge prior to this interaction or whether she constructed it in her attempt to answer M's question. Nevertheless, L's questions prompted M's construction and/or elaboration of this incorrect knowledge piece. L accepted M's explanation and attempted to map it into a drawing (in Turns 6 & 8). She then questioned M about the exact destination (Turns 10 and 12) probably to verify what M had said earlier. M responded to L's questions first by reading the text, "Returns to the left atrium of the heart" (Turn 11), and then by generating additional inference (Turn 13). What the text intended to convey was that oxygenated blood *from the lungs* returns to the left atrium of the heart, but both M and L interpreted this to mean that blood *from the left ventricle* returns to the left atrium of the heart. After these exchanges, both seemed to have agreed that the blood flows from the left ventricle to the left atrium up through the heart. The partner did not question it and simply accepted it.

(2) *Case 2*. In another pair (Pair 1), the students both incorrectly inferred that there was a valve when blood entered the heart. There are four valves in the heart, two semilunar valves that separate the ventricle from arteries and two a-v valves that separate the atrium from the ventricle. The a-v valves are also called tricuspid (right side) and bicuspid (left side) valves. The a-v valves are described in the following three sentences in the text.

(23) One-way valves separate these chambers and prevent blood from moving in the wrong direction.
(24) The atrioventricular (a-v) valves separate the atria from the ventricles.
(25) The a-v valve on the right side is the tricuspid, and the a-v valve on the left is the bicuspid valve.

In this pair, the drawing made during the collaborative learning session along with the video-tape indicated that they misinterpreted Sentence 23. They thought that the valves described in Sentence 23 were different from the valves described in Sentences 24 and 25, so that the one way valves that text Sentence 23 described were located at the entrance of the heart, while the valves described in Sentences 24 and 25 were located between the atrium and the ventricle. They inferred these additional valves and drew six valves in the heart, which was clearly shown in the drawing they made during the collaborative learning session (see Figure 8).

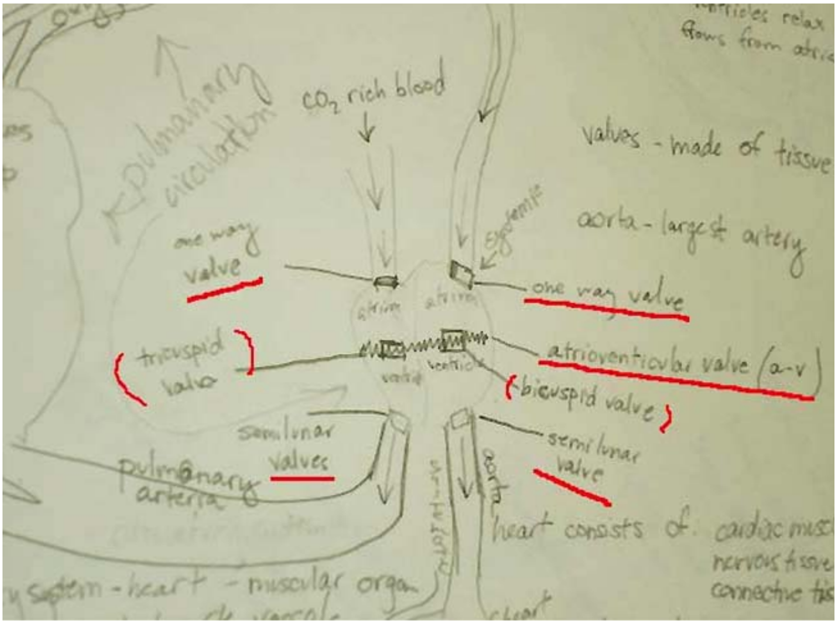


Figure 8. Pair 1's drawing made during the collaborative learning session (thick underlines and parentheses are added).

Discussions

Although it has been generally assumed in the literature that collaboration leads to knowledge convergence, the extent of knowledge convergence has never been assessed in a clear-cut manner. In this study, we operationalized knowledge convergence as an increase in common knowledge and quantitatively assessed how much knowledge convergence occurred after collaborative learning. Even though the extent of convergence was modest, the overall pattern of the results confirmed Roschelle's (1992) earlier finding that knowledge convergence occurred during collaborative learning. We also undertook a series of analyses to determine whether the obtained convergence could indeed be attributed to collaborative interaction. The results showed that collaborative interaction, rather than some other factors related to the situation (e.g., shared learning texts), was responsible for the common knowledge construction. Students not only possessed significantly more common knowledge after collaboration, but also shared inferred and incorrect knowledge that was not explicitly given in the learning materials. Real and more interactive pairs constructed more common knowledge than nominal and less interactive pairs. The dialogues and drawings that they made during collaboration also supported this conclusion.

Although convergence did occur in this study, given the strong claim of convergence in the literature, the extent of convergence obtained in this study was quite modest. Few existing studies quantitatively assessed knowledge convergence, and it is difficult to judge whether the amount of convergence obtained in this study is more or less than what can be expected in this kind of collaborative learning situation. However, Fisher and Mandl (2005) recently used the method developed in this study and reported similar results. In their study, dyads shared more knowledge overall, but the degree of convergence was not substantial either. Only a small portion of knowledge (less than 20%) was actually shared in all conditions. Thus, it seems that the modest amount of convergence obtained in this study is the norm rather than the exception in this kind of unstructured naturalistic collaborative learning situation.[4]

The discrepancy between the impression of strong convergence assumed in the literature and the results of this study as well as Fischer and Mandl (2005) seems to have occurred for the following three reasons. *First*, existing studies did not take into account the shared inputs and task environments that learners are exposed to together. As pointed out earlier, shared input is an important source of common knowledge. Because it is difficult to separate the influence of environment inputs and interaction, one can easily mistake convergence due to shared input as convergence due to interaction, that is, shared construction.

Second, many existing studies like Roschelle (1992) have estimated knowledge convergence based on students' conversation alone. If one assesses convergence solely based on what students seem to agree on during conversation, most pairs would appear to reach a relatively good level of agreement. However, as we pointed out earlier, what they agree on is not necessarily what they actually share. They may agree because they do not want to embarrass their partner by confronting them or because they do not want their partner to know that they didn't understand the materials. Even when there are no such social concerns and genuine agreements occur, the contents of conversation are not always encoded and processed sufficiently to become a part of the individual's representation. For this to occur, one often needs to do more than paying attention to and acknowledging a contribution. An active effort to explain and integrate the contributions with existing representation is needed. When one fails to process the content of the contribution fully, the information may appear to be shared, but it is not integrated with the individual's representation and remains unshared.

Lastly, we often assume that mainly convergent processes are in operation during collaborative learning, but it is important to note that divergent processes are also in operation (Ickes & Gonzales, 1996). We have seen in this study that some of the students who shared their initial model diverged at the post-test, and some of the knowledge pieces that were shared at the pre-test were not shared at the post-test. The pre-test sharing was a coincidence rather than a result of interaction, but even though it was a coincidence, the fact that pairs with similar initial representations ended up with different final representations even when they worked on the same learning materials suggests that collaborative processes can make partners diverge from, as well as converge toward, each other. This divergence seems to occur for various reasons. If students process each contribution to a different degree so that one pays more attention to certain parts of the dialogue while the other pays more attention to other parts of the dialogue, such differential processing would lead them to construct different representations. Role differentiation during collaboration could also lead to divergence. If one serves as a tutor while the other serves as a tutee, or if one serves as an information collector while the other serves as an information analyzer, such role assignment during collaboration could lead them to focus on different aspects of the task and construct divergent representations. The might have been the reason why evidence of convergence was difficult to obtain in tutoring situations (Chi, Siler, & Jeong, 2004; Graesser et al., 1995).

This paper examined one aspect of 'socially shared meaning', that is, what is held in common between interaction partners' representations. We were able to determine the extent and origin of knowledge convergence to some extent, but we believe that we need to consider three separate aspects of knowledge convergence in order to understand the notion fully. These three aspects are intimately related and often assessed together, but it is still meaningful to conceptualize them separately. The first aspect of knowledge convergence is the *process* of convergence. The question here is how the process of collaboration or other types of interaction enables knowledge convergence. The grounding process (e.g., Clark, 1996) or relevancy of turns (Jeong, 2002; Sperber & Wilson, 1996) may serve as a vehicle for achieving convergence, while role differentiation would not. A second aspect is the *outcome* of convergence. As we discussed earlier, there are multiple outcomes of collaborative interaction. Common knowledge and common ground are some of the examples of such outcomes. As a group of people interact with each other, similarities in members' representations increase as well as an awareness of the similarities. A third aspect to consider is the *source* of convergence. By source, we mean the cause or origin of the convergent outcome. As we pointed out earlier, the convergence emerges as a result of group interaction, but it is equally likely that it arises as a result of sharing the same input. In this study, we focused on the outcome and source of convergence, but a more comprehensive conceptualization of knowledge convergence is needed so that future research on this topic should address how different aspects of convergence interact with each other in more detail.

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Notes

1. Four students could not complete the study after they took the pre-test. Two students already had accurate models (either Double Loop-1 or Double Loop-2), and another two students had personal experiences that could interfere with the study (one student recently had open-heart surgery and another had been to pharmacy school and worked as a pharmacist before attending college).
2. The data was collected in the Spring and the Summer semesters. Five students signed up too close to the end of the semester and could not be paired with other students (of the same gender and race) before the semester was over.
3. An additional four questions called *Historical Misconception Questions*, part of the original materials used in Chi et al. (1994), were used initially, but not reported in this paper because they were not relevant to the common knowledge analyses.
4. Although we believe that the kinds of strong convergence envisioned in the literature occurs rather infrequently and that the extent of convergence is usually modest, the results from this study should be evaluated within the specific context of

the study since some of its methodological features might have contributed to the modest amount of convergence. *First*, students (except one pair) did not know their partner prior to collaboration in this study. Although they had quite a number of similarities as college students and had some time to get to know each other before collaboration started, having to work with a stranger might have prevented them from engaging in more active collaboration. Since friendship could affect collaborative dialogue (Azmitia & Montgomery, 1993), more sharing might have been possible if students had known each other better. *Second*, although students in this study did not know much about the human circulatory system, the material used in this study was initially written for 8th graders and might have been too easy for college students. If the materials were more challenging, students might have collaborated more, seeking each other for help to fill the gap in their understanding. *Third*, the task used in this study, text comprehension, might be more prone to individualistic rather than collaborative work. Although text comprehension is often done collaboratively, it is true that it is more often carried out individually. Such prior experience of individualistic text comprehension activities have biased students to engage in more individualistic activities. This would be especially the case if student's learning styles are already individualistic. *Fourth*, our simple instruction for the collaborative learning session might have been insufficient in ensuring active collaboration. Students often do not know how to collaborate effectively. As a result, their interaction frequently remains at a superficial level (Jeong, 2002). A more elaborate and detailed instruction might have helped students to overcome their inexperience with collaborative work better.

Appendix: Instruction for collaborative learning session

Today you will be working together to learn about the human circulatory system. Your goal is to understand the circulatory system, that is, to understand what the parts are, how they each work, how the system as a whole works, and what its purpose is. You will be reading excerpts from a high school biology textbook. The text will be presented one sentence at a time so that you can think about each new piece of information and how it fits into your understanding of the circulatory system. You are allowed to look back to previous pages, and you may take notes or draw pictures. However, the text and your notes will not be available when you are tested.

Please read each line of the text aloud and discuss it with your partner. Explain out loud to your partner what that line means to you and how it relates to what you already know about the circulatory system. You might already know some useful information that your partner does not. It is important to talk about things even if they seem unimportant. It is very important for you to work together as a team to help each other to learn the materials. Talk over differences in your ideas or explanations and try to reach a shared understanding.

I have included a few sample questions to give you some ideas of what kinds of questions will be asked later. Try to learn the material in such a way that both of you can answer them at the end of the session. The answers to these questions may not be directly stated in the text, and you might have to make some inferences to answer them correctly.

Sample questions

(1) From the heart, where does blood travel in pulmonary circulation?
(2) Why is it less dangerous for a capillary to get clogged than an artery?
(3) What causes the black and blue mark you get when you run or bump into something?

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