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Collaborative learning processes associated with high and low conceptual progress

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Abstract. Computer-Supported Intentional Learning Environments (CSILE) is a database system in which learners collaboratively construct the knowledge represented in the database. This study examined how students in a grade 5–6 classroom built their classroom database on a science topic, 'electricity,' and differences in activities between high- and low-conceptual-progress students. This categorization of students was based on the amount of progress in understanding exhibited over the course of work on the electricity unit, and was not significantly related to standardized achievement test performance. As an analytic tool, Activity Theory, as explicated by Leontiev (1981) was used to describe students' activities mediated by the computer system. Two different levels of student activities were examined: (1) cognitive actions, in which students intentionally pursued cognitive goals; and (2) computer operations, used to attain these goals. In addition, two different psychological planes of collaborative work were considered: the solo pane, in which students mainly focus on their own inquiries, and the joint plane, in which they focus on improvement of the classroom knowledge as a whole. Comparisons of activities between high- and low-conceptual-progress students showed: (1) that high-conceptual-progress students were more concerned with constructing their knowledge centered around problems, whereas low-conceptual-progress students were more involved in accumulating referent-based knowledge; (2) that high-conceptual-progress students were significantly more likely to construct their knowledge by involving in interactive information flow between problem-based and referent-based knowledge; and (3) that high-conceptual-progress students more frequently used the graphics medium in the database to represent problem-based knowledge.

Recent studies of human cognition treat human beings as agents in a distributed cognitive system rather than as independent cognitive systems. The cognitive system is considered to be distributed over physical objects, semantic tools, and other people, all of which play a part in the accomplishment of cognitive tasks. This new perspective on human cognition suggests a new level of analysis of cognitive processes in which tool-mediated cooperative work plays a central role (Salomon, 1993). Studies of computer-supported cooperative work show that a computer-network system provides a useful way for people to function as a distributed cognitive system in conducting complicated tasks (e.g., Galegher, Kraut & Egido, 1990). Partly on the basis of results from studies in work places, educational researchers began experimenting with computer-supported cooperative learning environments (see Pea & Gomez, 1992 for a review).

'Computer-Supported Intentional Learning Environments' (CSILE) is a database system which facilitates classroom learning in such a distributed manner. CSILE is designed to support students' intentional learning as progressive problem solving (Scardamalia & Bereiter, 1991; 1994; Scardamalia, Bereiter, McLean, Swallow & Woodruff, 1989). Students store different types of knowledge representations as texts or graphics in the database. They assign different categories of thoughts to their notes, such as 'problem,' 'what I already know,' 'new learning,' and 'my theory.' These categories of thoughts are intended to introduce a level of metacognitive reflection into students' work with knowledge and to provide some scaffolding for a problem-solving approach to learning (Scardamalia et al., 1989). Thus, students can make use of CSILE as a tool for controlling their executive processes in learning.

All notes produced by students on a CSILE network go into a single public database, where they are available to the other students. Every activity in CSILE is thus to some extent interpersonal. This leads students to shared interpersonal representations of knowledge. Furthermore, students can easily do commentaries on others' notes. This function has a potential to facilitate learning as problem solving at the interpersonal level. Students can be involved in others' problem-solving activity by taking part in various types of reflective activity on the others' knowledge. In these ways, CSILE can support asynchronous cooperative work on students' own knowledge and understanding (Cohen, 1994; Oshima, 1994; Scardamalia & Bereiter, 1994).

However, these characteristics of a distributed cognitive system in CSILE do not guarantee that every student recognizes his/her learning as progressive problem solving through collaborative work. Although empirical studies which compare CSILE classrooms with traditional classrooms indicate positive overall effects on student intentional learning (e.g., Scardamalia, Bereiter, Brett, Burtis, Calhoun & Smith-Lea, 1992), some case studies (e.g., Oshima, 1994) show that students' awareness of CSILE as a cognitive tool for their intentional learning is quite different in its quality between high-conceptual-progress and low-conceptual-progress learners in the learning environment. Research on computer as partner of learners' cognition suggests the same problem (e.g., Norman, in press, in everyday situation; Salomon, Perkins & Globerson, 1991, in educational technologies; Winograd & Flores, 1986 in human-computer interaction). A common message across studies is that cognitive processes mediated by technologies are quite various. Thus, individual differences in the cognitive activities mediated by collaborative learning technologies are an important problem to investigate.

We use Leontiev's (1981) 'three strata of activity' as an analytic framework for examining learners' computer-mediated activity. Leontiev (1981) proposes that human activity consists of three different strata: (1) activity-motive,

(2) action-goal, and (3) operation-condition (Leontiev, 1981; Wertsch, Minick & Arns, 1984; Wells, 1994). *Activity* is a global stratum represented by its motive, which gives a general direction to behavior. Learning is an activity whose motive is to enable learners to become mature members of their cultural communities and to further develop the communities themselves (J. S. Brown et al., 1989; Collins et al., 1989). *Action* is a lower stratum, which is identified by a specific goal to be attained. An activity consists of actions that attain specific goals to satisfy the motive of the activity. For instance, learning activity is made up of many actions to attain goals – identifying what a problem is, collecting information resources, determining what information is needed, considering how the information is applied to the problem, and so on. *Operation* is a still lower stratum consisting of routinized behaviors used in carrying out actions. In every human behavior, each stratum is made up of a hierarchy of sub-strata. A global activity is composed of several sub-activities each of which has several hierarchies of actions and sub-actions. Each sub-action also has hierarchies of operations and sub-operations depending on conditions.

Particularly, with respect to the 'action-goal' and the 'operation-condition' strata, it is important to see how learners make use of available tools for their learning activity. As Leontiev (1981) argues in his paper, different operations, depending on different motives, may be used to carry out the same actions (e.g., Wertsch et al., 1984). Also, the same operations may be used to attain quite different actions. That means in this case that learners' motives in learning influence which actions they take to construct knowledge in the database and how they operate the system. Thus, the analysis of the action stratum and the operation stratum of learning activity provides us with an organized picture of a distributed cognitive system of learning activity in CSILE.

In this study, the two strata, action and operation, are defined as follows: Actions in CSILE that we examined consist of (1) representing knowledge in the database, and (2) coordinating the represented knowledge to create more elaborated knowledge. Operations related to these actions consist of computer operations used in representing and elaborating knowledge. The operations we examined were (1) generating a note, (2) revising a note, (3) monitoring previously written notes, (4) searching other learners' notes, and (5) commenting on others' notes.

Although all activity in CSILE may be viewed as interpersonal, two different planes of learning activity can be identified within the interpersonal space. The first is the *solo plane*, in which learners are engaged in advancing their knowledge through their own inquiries. The second is the *joint plane*, in which learners are engaged in collaborative construction of knowledge through interaction with others. These two planes of collaborative learning are well coordinated in expert communities (Cicourel, 1990; Hutchins, 1990). Individuals in the communities of practice acquire expertise through their contribution to cooperative work. Thus, the coordination of the two planes is considered to be critical to collaborative learning activity.

In examining learners' actions in the two planes of collaborative learning in CSILE, we made use of a distinction between problem-centered and referent-centered knowledge as defined by Bereiter (1992). The distinction is only indirectly related to learning methods. To put it briefly, the distinction may be said to pertain to how knowledge is indexed in the mind. Referent-centered knowledge is indexed according to what it is about. Problem-centered knowledge is indexed according to what it is good for. In the context of the present study, where students were working on a unit on electricity, with the objective of understanding how electricity works, referent-centered knowledge would be knowledge indexed according to the topic, 'electricity.' Problem-centered knowledge would be knowledge indexed according to its relevance to understanding how electricity works. Both kinds of knowledge are important. Students would need to accumulate a certain amount of knowledge *about* electricity before they would be in a position to recognize and organize knowledge according to its explanatory value. Thus, with students who make progress in understanding, one would expect to see students constructing problem-centered knowledge on the basis of referent-centered. We categorized learners as showing high conceptual progress or low conceptual progress depending on how much progress they showed over the course of the unit in their understanding of how electricity works. Then, we examined differences in their learning activity, with particular attention to their construction and accumulation of problem-centred and referent-centred knowledge.

Following the analysis of learners' actions, we analyzed learners' computer operations corresponding to the actions. Learners' manipulation of CSILE was automatically recorded as tracking files which show us when and what they did to attain goals of their actions. By examining the frequencies of various relevant computer operations, we can examine whether high-conceptual-progress and low-conceptual-progress students differed in their usage of the database system. Finally, we discuss a relationship between learners' actions and computer operations, and conclude by suggesting ideas on improvement of computer-supported learning environments.

Method

Subjects

Twenty-nine fifth- and sixth-grade students (13 males and 16 females) in a classroom in a Toronto public school participated in this study as part of their regular curriculum. Their mean CA was 136.5 months (*SD* = 7.0 months).

Curriculum description

The unit of curriculum examined in this study was electricity. This unit was composed of two sub-units: in the first unit, students were divided into groups of variable size and conducted experiments in which they observed electrical phenomena. They were expected to generate inquiries for further learning in CSILE based on these experiences. The experiments, which were prescribed as part of a packaged science kit, dealt with the following: (1) different types of circuits, (2) conductors and nonconductors, (3) electromagnets, (4) hand generators and (5) electric flow in several types of water solutions.

In the second sub-unit, students worked collaboratively through the use of CSILE notes. They were instructed by the teacher (1) to first generate a note titled 'what I think about how electricity works,' (2) to generate problems or questions to guide their inquiries for their learning in the next note, titled 'what I do not know,' and (3) to develop their explanations of how electricity works based on their work on reference materials and collaborative learning. The teacher encouraged the students to use the computer database to develop their understanding through database communication. The task in this second sub-unit was to develop an understanding of how electricity works through creating a classroom database as public representations of knowledge. Thus, the activity system in this second sub-unit was composed of the following main actions: (1) work with reference materials, (2) discussion of the topic among the learners and the teacher in the classroom, (3) work in the computer database. This study particularly focused on the third part of the second sub-unit, the analysis of student activity mediated by the database system.

There were eight microcomputers in the classroom, networked through a CSILE server. The CSILE-based portion of the electricity unit lasted for six weeks in the spring of the academic year, during which students constructed a community database by writing notes, revising previous notes, searching others' information to obtain ideas and information, commenting on each others' notes, and so on. Notes could be in either text or graphic form. Boolean searches of the database could be carried out according to a variety of criteria, including author and keywords. Authors were automatically notified when there were comments on their notes.

Data source

All learners' manipulations in the computer database were recorded in computer tracking files. Tracking information relevant to the present study included (1) time when each learner used the computer, (2) contents of texts or graphics created by learners, and (3) learners' operations in the computer system, such as entering new notes and comments, and carrying out database searches. Table 1 shows an example of a CSILE text note with selected tracking information attached: A learner started his computer communication and wrote a new note about the study topic. The first line 'CS 91-02-27-12:27:30 301' specifies the starting time of the computer session. In this case, the learner started his computer session at 12:27:30 on Feb. 27, '91. The last number on this line, '301,' specifies his user number. The second line 'NB 91-02-27-12:27:31' identifies the starting time of note session. Records of note writing, note editing, note searching and/or commenting follow the session-start line. In Table 1, the third line 'NW 91-02-27-12:53:02 2163' means the time of opening a new note window. The last number '2163' specifies the note number. Following these lines, the content of the note appears. Other activities such as note editing, note searching, and commenting were recorded in the same format as note writing. In note editing activity, the tracking file recorded time to start editing, a note number to edit, and an edited version of note content. In note searching activity, the tracking file recorded starting time, note attributes specified in the search, number of retrieved notes, and time of opening each retrieved note. In commenting activity, the file recorded similar information, plus a note number indicating the note to which the comment was attached.

Classification of students as high- and low-conceptual-progress learners

We defined high-conceptual-progress learners as learners who improved their explanatory discourses on topic-related phenomena during the course of the unit. It did not necessarily mean that the high-conceptual-progress learners finally reported higher quality domain-specific knowledge than did low-conceptual-progress learners. Rather, we evaluated the processes of learning by which learners critically changed their explanatory discourses in the database. Students who improved their conceptual framework of explanatory discourse from their initial framework of discourse were categorized as high-conceptual-progress learners. The remainder of the students, whose explanatory discourses on their inquiries were not conceptually changed during their learning, were classified as low-conceptual-progress learners.

Table 1. An example of tracking file.

```
CS 91-02-27-12:27:30 301
NB 91-02-27-12:27:31
NW 91-02-27-12:53:02 2163
A-> 91-02-27-12:53:02 2163
I THINK ELECTRICITY WORKS LIKE THIS:
First you need some source of energy, which is contained in batteries and can
be made by turning something very rapidly
like with a hand generator.To get the energy from the source to the light bulb
you need an electricity conductor.The energy then flows through the electricity
conductor at an  amazing speed.
When the electricity goes through the tiny wires in the light bulb you can see
the electricity and that is how I think the bulb is lit.
When the electricity comes out of the light bulb it goes in to a wire and then
back to the source where it repeats the circle until the bulb is either turned
of burned out.          <-A
TO 91-02-27-12:53:02 2163 Electricity
```

Two raters assessed the improvement of learners' problem-centred knowledge from the beginning to the end of their learning. Eight learners among twenty-nine in a classroom were independently assessed as high-conceptual-progress ones by the two raters, and the remaining were defined as low-conceptual-progress. Inter-rater reliability was over 0.90.

Data coding scheme

Learning processes in the database were described at two different levels: (1) action level and (2) computer operation level. In the action level, we focused on how learners constructed knowledge represented in the database; in the computer operation level, how learners used computer functions to conduct their cognitive actions was examined.

Learners' actions in CSILE

In examining CSILE activity at the action level, we focused on knowledge items and their relationships. A group of sentences was treated as a separate knowledge item. A graphic was treated as a single knowledge item unless it contained text of more than one sentence. For example, note content in Table 1 was divided into two items of knowledge. The first item consisted of first three sentences which showed the student's knowledge of what we need to create an electric circuit. The second consisted of last two sentences which showed the student's mental model of how electricity works. Three types of knowledge were categorized. The first was *referent-centred knowledge*. Typically, this was definitional or descriptive information about the discourse topic. In the note in Table 1, the statement that energy 'flows through the electricity conductor at an amazing speed' exemplifies referent-centred knowledge. It is relevant to the topic, the lighting of a light bulb, but not to the problem, which is to explain what makes the light bulb light. The second was *problem-centred knowledge*, which is knowledge whose relevance to the problem at hand is either stated or is obvious from the context. The item in Table 1, 'When the electricity goes through the tiny wires in the light bulb you can see the electricity and that is how I think the bulb is lit [sic],' for instance, is clearly information thought by the student to contribute to solving the problem of what makes the light bulb light. As this item illustrates, accuracy and quality are not considerations in distinguishing between referent-centred and problem-centred knowledge, only apparent intent and relevance to objectives are. The third was *metacognitive knowledge* – knowledge relevant to the control of executive processes rather than to the substance of the discourse. Although metacognitive knowledge is seldom explicitly represented in ordinary writing on scientific topics, it appears with some frequency in CSILE notes, possibly because of its being encouraged through the labeling of types of thinking.

Relationships among knowledge items, rather than characteristics of the individual items, should be the most important indicators of learning activity leading to conceptual progress. Two types of knowledge connections were identified in this study. The first was *knowledge-widening*. These are connections in which the new knowledge item is simply added on to the knowledge already represented, resulting in an increase in quantity without progress toward solving a stated problem. This does not mean that items are added mindlessly, however. The new information may provide new examples or applications of knowledge already represented. The second type of connection was *knowledge-deepening*. This type of connection shows that a learner represents a higher level of knowledge constructed on preceding knowledge represented in the database, e.g., a revised conjecture, a generalization over previously reported examples, or clarification or elaboration of a problem-centered idea.

Learners were engaged in collaborative knowledge building in the joint plane as well as the solo plane. Activity in the joint plane was carried out by students' accessing others' notes. In examining this activity at the action level, we focused on the relationship between knowledge items in retrieved notes produced by other students and new knowledge items produced by the student who retrieved them. As in the solo plane, students could build on preceding knowledge items in a knowledge-widening or in a knowledge-deepening way.

Commenting was an important part of work in the joint plane. We categorized contents of learners' comments as one of the following: (1) knowledge-widening, (2) knowledge-deepening, or (3) writing-based. Knowledge-widening comments were ones considered to promote a knowledge-widening action by an author of the original note. Knowledge-deepening comments were considered to promote a knowledge-deepening action by the original author. Writing-based comments referred to the others' writing rather than knowledge content. The most typical writing-based comments dealt with spelling or grammar.

Learners' computer operations in CSILE

Various analyses of computer operations, based on tracking data, will be explained in the course of presenting results.

Coding procedure

From the computer tracking files, the notes for each student (including graphics) were compiled into a table (an example is provided in Appendix A). Each table consisted of a sequence of notes by a single learner in a study topic. A boundary between notes was represented as a dashed line. Each section of a note included its generation (NW) or revision (NE), note number, and content of the note. For written discourse in a note, each sentence was numbered, and a boundary between paragraphs was represented by a blank line. Graphics were presented in different sheets. Two independent raters categorized sentences and graphics reported by ten randomly selected learners into the three types of knowledge. One of the two raters evaluated all learners' notes twice by two-week interval. The inter-rater reliability and the inter-period reliability were over 0.90.

Learners' joint activity was also tabulated (see Appendix B). Each table consisted of search strategies used by learners, and numbers of accessed notes. A search session boundary was represented as a dashed line, and a boundary between notes in a single session was represented as a blank line.

Results and discussion

In this section, we report data analyses in two parts, corresponding to the *action* and *operation* levels recognized in Activity Theory; i.e., analyses of actions related to cognitive goals and analyses of computer operations in CSILE. Within each part, analyses are further divided into those pertaining to the solo plane and those pertaining to the joint plane of activity.

Differences in cognitive actions between high- and low-conceptual-progress learners

Differences in representing knowledge

Scores on the Canadian tests of basic skills in writing, reading, and vocabulary. As standardized measures of learners' skills in written discourse, the three scores (standardized percentiles based on a sample provided by the manual) were used. Since CSILE learning was based on written discourse, learners' basic skills in reading and writing might affect usage of the database system and consequently account for differences between high- and low-conceptual-progress students. To test this possibility, correlational relationships between the basic skills and the numbers of knowledge items in three categories (referent-centered, problem-centered, and metacognitive) were examined. Scatter plots of learners did not indicate any relationships. The two groups of learners were then compared on the three basic skills scores, using a one-way multivariate analysis of variance. No significant effects were found (Wilks' Lambda = 0.84, $p > 0.05$), and therefore we concluded that the learners' basic skills in written discourse in this sample were not a significant factor in their usage of CSILE.

Numbers of knowledge items. To examine differences between high- and low-conceptual-progress learners in generation of knowledge items, planned comparisons in a 2 (Type of Learners) $\times$ 2 (Type of Knowledge: Problem-Centred or Referent-Centred) design on numbers of knowledge items were carried out. High-conceptual-progress learners were found to produce more of both kinds of knowledge items: $F(1,27) = 35.4$ for problem-centred knowledge and $F(1,27) = 6.6$ for referent-centred knowledge, $p < 0.05$ in both cases. In comparisons between the two types of knowledge within each group of learners, different patterns were found, as shown in Figure 1. High-conceptual-progress learners did not show a significant difference in frequency between the two types of knowledge, $F(1,27) = 0.1$, $p > 0.05$, whereas low-conceptual-progress learners generated significantly more referent-centered than problem-centered knowledge items, $F(1,27) = 13.8$, $p < 0.05$.

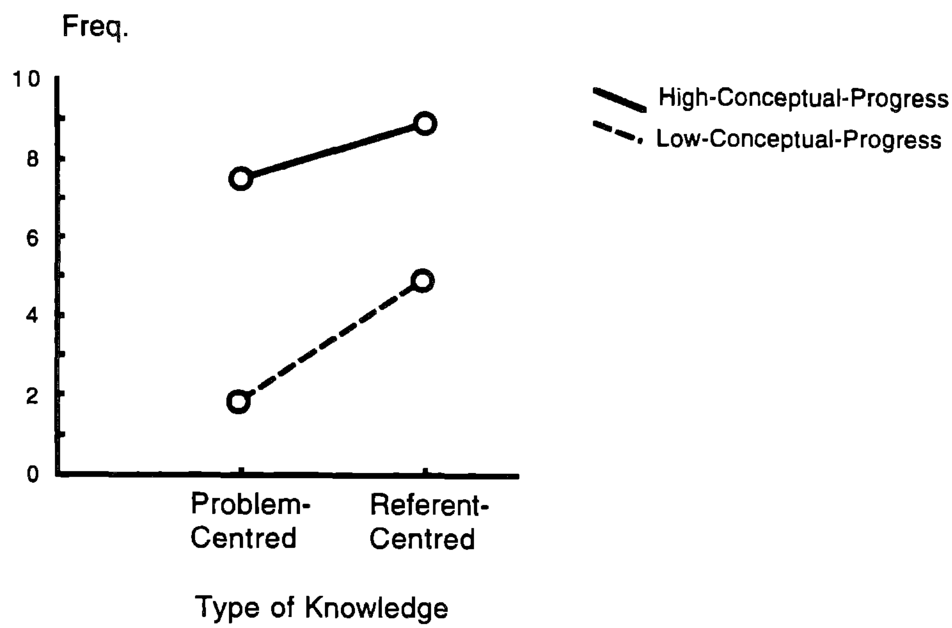

Figure 1. Mean frequencies of knowledge items represented by learners in CSILE.

Differences in organizing knowledge in the solo plane

Proportions of different types of knowledge change. Here, we examined a change in learners' knowledge represented in the database. Change was coded on the basis of the kind of knowledge represented in an item and its relation to the kind of knowledge represented in the immediately preceding item by the same student. Thus, there were eight possible categories of knowledge change, based on two types of knowledge connections, two types of represented knowledge, and two types of previous knowledge: (1) widening change in referent-centred knowledge based on problem-centred knowledge, (2) widening change in referent-centred knowledge based on referent-centred knowledge, (3) deepening change in referent-centred knowledge based on problem-centred knowledge, (4) deepening change in referent-centred knowledge based on referent-centred knowledge, (5) widening change in problem-centred knowledge based on problem-centred knowledge, (6) widening change in problem-centred knowledge based on referent-centred knowledge, (7) deepening change in problem-centred knowledge based on problem-centred knowledge, and (8) deepening change in problem-centred knowledge based on referent-centred knowledge.

Since there were significant differences in frequencies of referent-centred and problem-centred knowledge between the two groups of learners, frequencies of the eight types of knowledge change were converted to percentages, based on the proportion of knowledge items of a particular type (problem-centred or referent-centered) that belonged to a particular change category. Thus, if a learner represented five items of referent-centred knowledge, and three of them were by knowledge-widening changes based on preceding problem-centred knowledge, then the percentage score for category 1, above, would be 3/5 × 100, or 60. In the case of categories 2, 4, 5, and 7, where a knowledge item was based on a preceding item of the same type, the denominator was reduced by 1, because it would be impossible for the first knowledge item of a type to belong to one of these categories. Some learners did not represent any problem-centred knowledge.

Because no low-conceptual-progress learners showed deepening change in problem-centred knowledge based on preceding referent-centred knowledge, the comparison was conducted by a nonparametric analysis in a 2 (Type of Learners) × 2 (Presence of the Knowledge Change Pattern) frequency table (Table 2). For seven other proportional scores, *t*-tests were carried out with type of learners as a between-subjects factor. Results were summarized in Table 3. Significant results were found in comparisons of four proportional scores. High-conceptual-progress learners showed significantly higher percentages than did low-conceptual-progress learners in the following categories: deepening change in referent-centred knowledge based on preceding referent-centred knowledge; deepening change in problem-centred knowledge based on preceding problem-centred knowledge; and deepening change in problem-centred knowledge based on preceding referent-centred knowledge. Low-conceptual-progress learners, on the other hand, were more likely than high-conceptual-progress learners to widen problem-centred knowledge based on preceding problem-centred knowledge.

The results showed that in comparison with low-conceptual-progress learners, high-conceptual-progress learners engaged in more knowledge-deepening actions particularly in problem-centred knowledge. They were also involved significantly more in the deepening change in referent-centred knowledge based on preceding referent-centred knowledge. In contrast, low-conceptual-progress learners seemed more concerned with assimilating problem-centred knowledge. Thus the knowledge they constructed tended to be at the same level as the preceding knowledge item.

Differences in engagement in joint activities

Numbers of joint sessions. As a measure of how much learners were engaged in their joint activities, frequencies of joint sessions was counted. Joint sessions occurred when students searched other students' notes and read them. A *t*-test showed no significant difference between high- and low-conceptual-

Table 2. Frequencies of high- and low-conceptual-progress learners who showed deepening change in problem-centred knowledge based on previous referent-centred knowledge or not.

Type of Learners	Deepening Problem-Centred Knowledge Change	
	Showed	Did Not Show
High-Conceptual-progress	4	4
Low-Conceptual-progress	0	15

A nonparametric test showed a significant proportional difference between high- and low-conceptual-progress learners who showed deepening change in problem-centred knowledge based on their preceding referent-centred knowledge, χ^2 (23) = 9.1 $p < 0.05$.

progress learners in mean number of joint sessions, $t(26) = 0.29, p > 0.05$ ($M = 4.6$, $SD = 3.5$ for low-conceptual-progress learners vs. $M = 5.0$, $SD = 2.0$ for high-conceptual-progress learners). From this we infer that the two groups of learners did not differ in overall amount of participation in joint activities.

Differences in response to others' knowledge

Both types of learners were found to be equally engaged in joint activities during their learning in CSILE. We here focused on contents of knowledge they accessed and responded to. In all cases, we counted only knowledge items in retrieved notes that, according to tracking data, remained on the learner's screen for at least 10 seconds as numbers of accessed items.

Types of accessed knowledge items. Proportions of three types of accessed knowledge items were analyzed. A 2 (Type of Learners) $\times$ 3 (Type of Knowledge) ANOVA on the proportional scores showed a marginally significant effect of Type of Knowledge, $F(1,17) = 2.6$, $p < 0.10$, and a marginally significant interaction effect, $F(2,34) = 3.3$, $p = 0.05$. Planned comparisons following the main analysis showed: (1) that high-conceptual-progress learners accessed more problem-centred knowledge than did low-conceptual-progress learners, $F(1,17) = 4.2$, $p < 0.10$; and (2) that high-conceptual-progress learners accessed more problem-centred and referent-centred knowledge than metacognitive knowledge, $F(1,17) = 6.7$, $p < 0.05$, and $F(1,17) = 3.3, p < 0.10$ respectively (Figure 2).

Table 3. Summary of comparisons of proportional scores of knowledge change in the solo-plane.

Proportional Scores	Means	
	Low-Progress	High-Progress
Widening Change in Referent-Centred Knowledge Based on Problem-Centred Knowledge (Ns = 15, 8)	9.0 (16.0)	6.7 (8.2)
Widening Change in Referent-Centred Knowledge Based on Referent-Centred Knowledge (Ns = 19, 8)	31.7 (35.5)	53.4 (33.4)
Deepening Change in Referent-Centred Knowledge Based on Problem-Centred Knowledge (Ns = 15, 8)	6.7 (25.8)	17.1 (14.1)
Deepening Change in Referent-Centred Knowledge Based on Referent-Centred Knowledge (Ns = 19, 8)	3.4 (8.1)	13.9 (13.3)**
Widening Change in Problem-Centred Knowledge Based on Problem-Centred Knowledge (Ns = 10, 8)	75.0 (37.3)	43.0 (14.1)**
Widening Change in Problem-Centred Knowledge Based on Referent-Centred Knowledge (Ns = 15, 8)	19.3 (36.3)	2.5 (7.1)
Deepening Change in Problem-Centred Knowledge Based on Problem-Centred Knowledge (Ns = 10, 8)	5.0 (15.8)	30.0 (26.3)**

Note. ** and * shows significant differences, $p < 0.05$ and $p < 0.10$ respectively. Numbers in parentheses show *SD*.

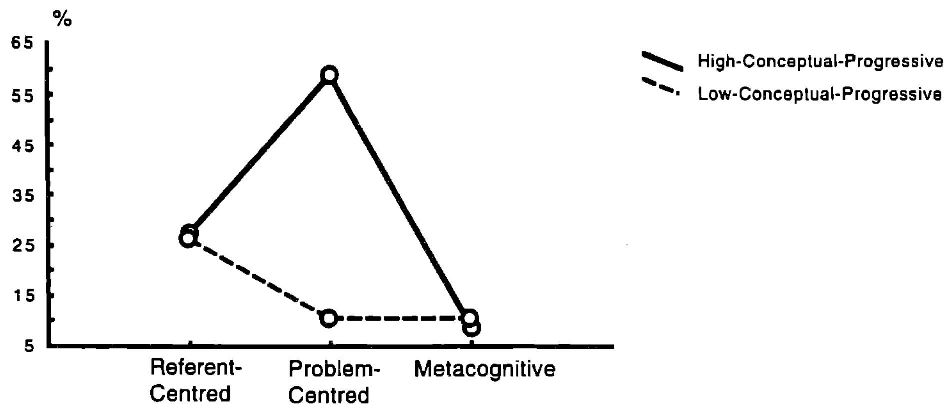

Figure 2. Mean proportions of knowledge accessed by learners in the joint-plane.

Allowing for the fact that effects were only marginally significant, Figure 2 suggests the following pattern: High-conceptual-progress learners were likely to be more concerned with problem-centred knowledge than referent-centred knowledge whereas low-conceptual-progress learners were more involved in referent-centred knowledge than problem-centred knowledge.

Proportions of knowledge change based on others' knowledge. Here, we examined the same two types of knowledge change as in the solo plane. However, the focus was on changes in knowledge based on knowledge represented in other students' notes. Because numbers of knowledge change based on others' knowledge were not frequent, the eight categories used in the solo-plane were merged into two categories: (1) deepening change in knowledge based on others' knowledge, and (2) widening change in knowledge based on others' knowledge. Chi-square analyses on frequency tables showed: (1) that significantly more high-conceptual-progress learners made knowledge-deepening changes than did low-conceptual-progress learners, χ^2 (23) = 5.8, $p < 0.05$ (Table 4); and (2) that the two groups of learners did not differ significantly in tendency to make knowledge-widening changes, χ^2 (23) = 1.3, $p > 0.05$ (Table 5).

Proportions of different types of comments. This was another measure of learners' coordination of others' knowledge. We focused on what types of comments learners did on others' knowledge. Because comments were not frequent, a nonparametric analysis was used. Each learner was categorized as either using or not using each of the following types of comments: (1) knowledge-widening, (2) knowledge-deepening, (3) writing-

Table 4. Frequencies of high- and low-conceptual-progress learners who showed deepening change in knowledge based on others' knowledge or not.

Type of Learners	Deepening Knowledge Change	
	Showed	Did Not Show
High-Conceptual-Progress	4	4
Low-Conceptual-Progress	1	14

Note. Five low-conceptual-progress learners were omitted from the analysis, because they did not show any attempt to get involved in their joint activities.

Table 5. Frequencies of high- and low-conceptual-progress learners who showed widening change in knowledge based on others' knowledge or not.

Type of Learners	Widening Knowledge Change	
	Showed	Did Not Show
High-Conceptual-Progress	4	4
Low-Conceptual-Progress	4	11

Note. Five low-conceptual-progress learners were omitted from the analysis, because they did not show any attempt to get involved in their joint activities.

based. Chi-square analyses showed: (1) no significant difference in the use of knowledge-widening comments; (2) a marginally difference in use of knowledge-deepening comments, χ^2 (23) = 3.6, $p < 0.10$; and (3) no significant difference in the use of information and writing-based comments. The results thus agree with the preceding results in suggesting that high-conceptual-progress learners tended to respond to others' knowledge in a knowledge-deepening manner (Tables 6, 7,and 8).

Table 6. Frequencies of high- and low-conceptual-progress learners who commented on others' knowledge in knowledge-widening way or not.

Type of Learners	Knowledge-Widening Comment	
	Showed	Did Not Show
High-Conceptual-Progress	3	5
Low-Conceptual-Progress	4	11

Note. Five low-conceptual-progress learners were omitted from the analysis, because they did not show any attempt to get involved in their joint activities.

Summary of differences in cognitive actions between high- and low-conceptual-progress learners

The results of the above analyses provided us with characteristics of high- and low-conceptual-progress learners in CSILE, and their differences in cognitive actions. Differences in actions are summarized in Figures 3 and 4 which respectively show us patterns of actions by high- and low-conceptual-progress learners. Each figure consists of two different planes of knowledge: (1) self-knowledge and (2) others' knowledge. Different sizes of knowledge circles show different amounts of engagement which learners manifested. Changes in knowledge are delineated by two different kinds of lines. A line with an arrow shows a knowledge-deepening link, and a line with a circle shows a knowledge-widening link. Bold lines represent kinds of knowledge links which were found significantly more often in one group than the other.

The resulting patterns may be summarized as follows: First, two groups of learners were concerned with different types of knowledge in their distributed systems with CSILE. Problem-centred knowledge had potentials which have learners engage in knowledge-deepening actions in CSILE. Second, they also retrieved different types of knowledge for their knowledge building. More retrieval of problem-centred knowledge was correlated with more advancement of learners' knowledge. Third, two groups of learners saw the same computer tool as different constructive arenas. Disposition to consider progressive change of knowledge based on previous ones was positively related to better advancement of learners' knowledge. A progressive movement between

Table 7. Frequencies of high- and low-conceptual-progress learners who commented on others' knowledge in knowledge-deepening way or not.

Type of Learners	Knowledge-Deepening Comment	
	Showed	Did Not Show
High-Conceptual-Progress	4	4
Low-Conceptual-Progress	2	13

Note. Five low-conceptual-progress learners were omitted from the analysis, because they did not show any attempt to get involved in their joint activities.

Table 8. Frequencies of high- and low-conceptual-progress learners who commented on others' knowledge in writing-based way or not.

Type of Learners	Writing-Based Comment	
	Showed	Did Not Show
High-Conceptual-Progress	2	6
Low-Conceptual-Progress	7	8

Note. Five low-conceptual-progress learners were omitted from the analysis, because they did not show any attempt to get involved in their joint activities.

problem-centred and referent-centred knowledge in a distributed system is considered a cognitive framework for knowledge building in CSILE.

The differences in cognitive actions between high- and low-conceptual-progress learners suggest differences in activities they engaged in. First, the results showed that the solo and the joint plane of activity were well coordinated in the high-conceptual-progress learners' knowledge building, whereas these two planes were treated as discrete by the low-conceptual-progress

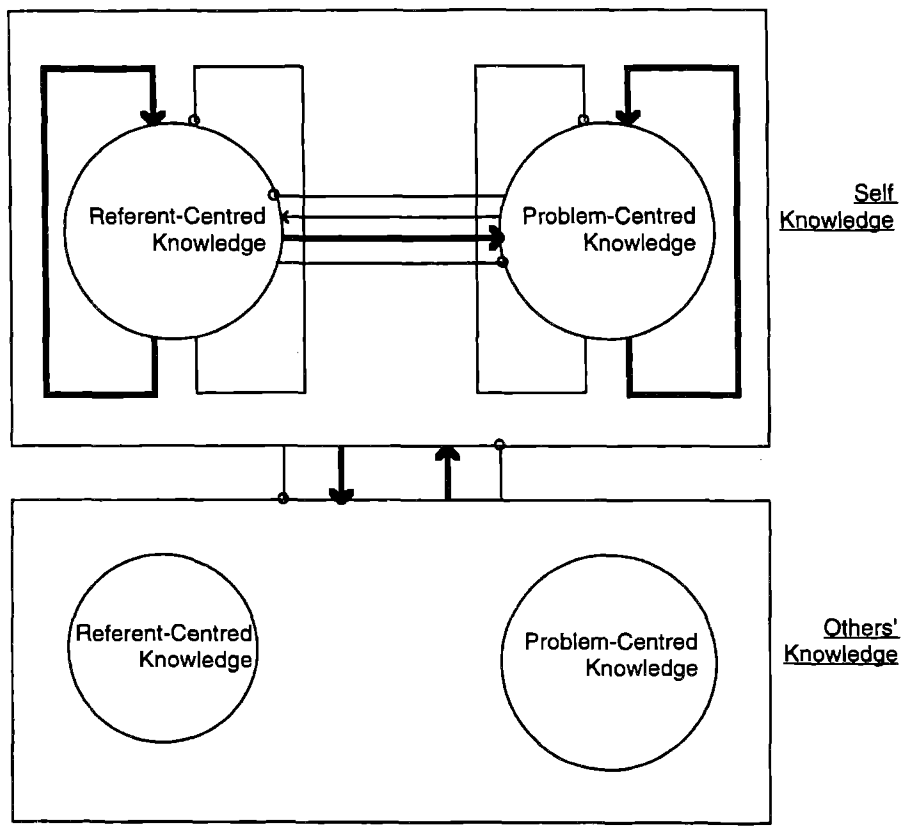

Figure 3. Cognitive actions by high-conceptual-progress learners in CSILE. Note. A size of circle shows significantly different amount of concern learners manifested in each area of knowledge. A larger circle means more concern by learners. Two types of knowledge change based on previous knowledge are represented as a line with a circle for knowledge-widening and a line with an arrow for knowledge-deepening. Bold lines represent knowledge change patterns which were significantly different between high-conceptual-progress and low-conceptual-progress learners.

learners. The high-conceptual-progress learners attempted to manipulate equally other learners' knowledge and their own knowledge in the joint plane of activity, and integrated them to create a higher level of knowledge. On the contrary, the low-conceptual-progress learners discriminated others' knowledge from their own knowledge. They were likely to get information that they had not had in their joint activities, but they did not attempt to integrate their own and others' knowledge. Thus, the high-conceptual-progress learners recognized their own and others' knowledge in the database as an object for knowledge building, and therefore they were engaged in an activity with others' knowledge as 'a tool for their collaborative construction of higher

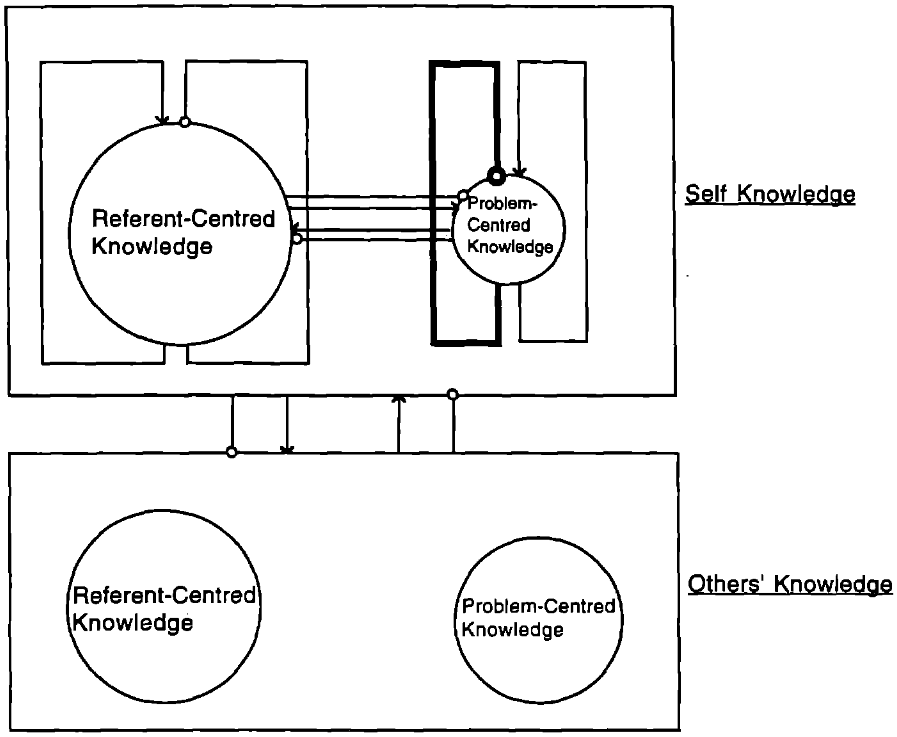

Figure 4. Cognitive actions by low-conceptual-progress learners in CSILE. Note. A size of circle shows significantly different amount of concern learners manifested in each area of knowledge. A larger circle means more concern by learners. Two types of knowledge change based on previous knowledge are represented as a line with a circle for knowledge-widening and a line with an arrow for knowledge-deepening. Bold lines represent knowledge change patterns which were significantly different between high-conceptual-progress and low-conceptual-progress learners.

levels of scientific explanations.' In contrast to this, the low-conceptual-progress learners recognized their self knowledge as discrete information and saw others' knowledge as an object for getting information, and therefore they were engaged in another activity with others' knowledge as 'new information.'

The differences in the motives of learning activities are nicely interpreted by Lotman's distinction of text functions in communication (Lotman, 1988; Wertsch, 1991). He argues that two different types of functions simultaneously exist in text. The first function is the 'univocal function' (Wertsch, 1991). In this function, information in text is unidirectionally transmitted from a sender to a receiver. The goal for the receiver is to understand or accept correctly what the sender says. The second function is the 'dialogical function' (Wertsch, 1991). In this function, meaning in text is constructed through interaction between a sender and a receiver. The goal for the receiver here is not simply to understand what the sender says, but to get involved in meaning construction of the text through interaction. From this point of view, low-conceptual-progress learners' communication in the database is considered to be weighted on the first, 'univocal function,' whereas high-conceptual-progress learners' communication is weighted on the second, 'dialogical function.' Thus, the high-conceptual-progress learners changed critically their scientific explanations through collaborative work in dialogical communication in CSILE.

Differences in computer operations between high- and low-conceptual-progress learners

So far, we have examined differences in cognitive actions between high- and low-conceptual-progress learners. The results suggested that high-conceptual-progress learners used CSILE as a tool for knowledge building whereas low-conceptual-progress learners used CSILE as a tool for recording their thoughts. In addition, high-conceptual-progress learners engaged more in dialogical processes of knowledge building in their joint activities, whereas low-conceptual-progress learners were involved in more unidirectional flow of information. Here, we analyzed another level of CSILE activity, computer operations. We focused on whether the two groups of learners conducted different operations to perform their different cognitive actions.

Computer operations in the solo plane of CSILE

In the solo plane of CSILE work, three kinds of computer operations were examined. The first was 'search-and-retrieve' of students' own notes. This operation would be instrumental to reflection and knowledge revision, and so was expected to be more frequent among high-conceptual-progress learners. The second was amount of knowledge represented per note. Learners could choose strategically to represent their knowledge and thoughts in various ways. If each single piece of knowledge was represented in a separate note, many notes would be produced, and it would be hard to review all the notes. However, since each note would represent a single idea, it would be easier to manipulate knowledge, discover connections, and so on. Therefore, average number of knowledge items represented in a note was examined. The third was relative use of the two media in CSILE – text and graphics – to represent knowledge. Research on mental models of scientific concepts has indicated that visual representations of scientific knowledge – e.g., mechanisms – facilitates learners' conceptual development (Gentner & Stevens, 1983). If graphics functioned as a medium for learners to represent their mental models, high-conceptual-progress learners would generate more problem-centred knowledge items in comparison with low-conceptual-progress learners.

Frequency of reviewing operations. A t-test on frequency of reviewing operations showed no significant difference between the groups of learners, $t(27) = 0.35, p > .05$ ($M = 15.5$, $SD = 4.8$ for high-conceptual-progress learners vs. $M = 14.0$, $SD = 12.1$ for low-conceptual-progress learners). Furthermore, a proportion of knowledge they reviewed in each review was examined. A t-test on individuals' average proportions of knowledge items showed no significant difference, $t(27) = -1.5, p > 0.05$ ($M = 33.6\%$, $SD = 7.9$ for high-conceptual-progress learners vs. $M = 43.9\%$, $SD = 19.1$ for low-conceptual-progress learners).

Number of knowledge items in a single note. Individuals' average numbers of knowledge items in a note were also examined. A t-test showed that high-conceptual-progress learners moduled more knowledge items per note than did low-conceptual-progress learners, $t(27) = 1.9, p < 0.10$ ($M = 1.4$, $SD = 0.2$ for high-conceptual-progress learners vs. $M = 1.2$, $SD = 0.2$ for low-conceptual-progress learners).

Frequency of knowledge items represented in two media. To examine how learners used two media available in CSILE, frequencies of different types of knowledge items in each medium were counted. Planned comparisons in 2 (Type of Learners) $\times$ 2 (Type of Knowledge) design on the frequencies of knowledge items in text- and graphic-medium were carried out. In comparisons in text-medium, high-conceptual-progress learners outperformed low-conceptual-progress learners in both types of knowledge items, $F(1,27) = 7.4$ for referent-centred knowledge and $F(1,27) = 26.4$ for problem-centred knowledge, $p < 0.05$ in both cases (Figure 5). On the contrary, in comparisons in graphic-medium, high-conceptual progress learners outperformed low-conceptual-progress learners in problem-centred knowledge, $F(1,27) = 28.7, p < 0.05$, but not in referent-centred knowledge, $F(1,27) = 0.03, p > 0.05$ (Figure 6).

Computer operations in the joint plane of CSILE work

In the joint plane, two computer operations were examined. The first was search strategy in the database. This was of interest because database search was a necessary preliminary to learners' joint activity. Information on strategies came from recording of the attributes students chose as search criteria. The second was number of others' knowledge items learners retrieved in their retrieving sessions. In cognitive action level, we analyzed proportions

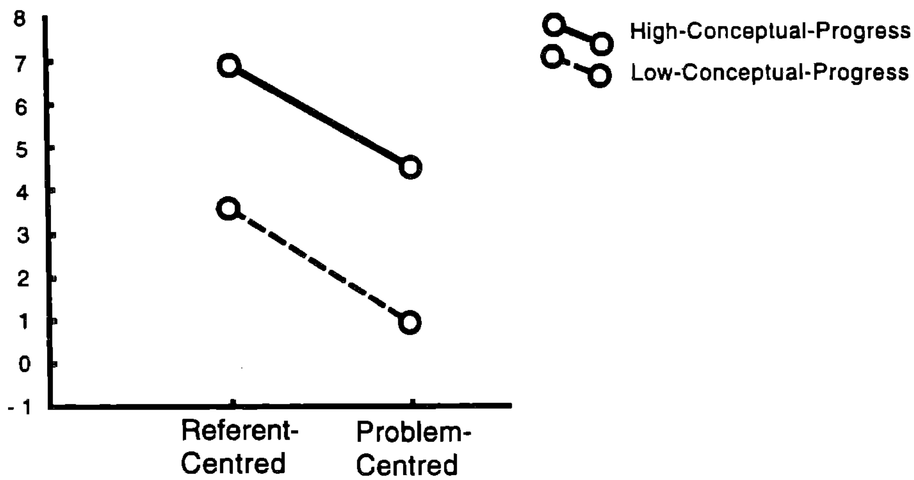

Figure 5. Mean numbers of knowledge items in text-medium of CSILE.

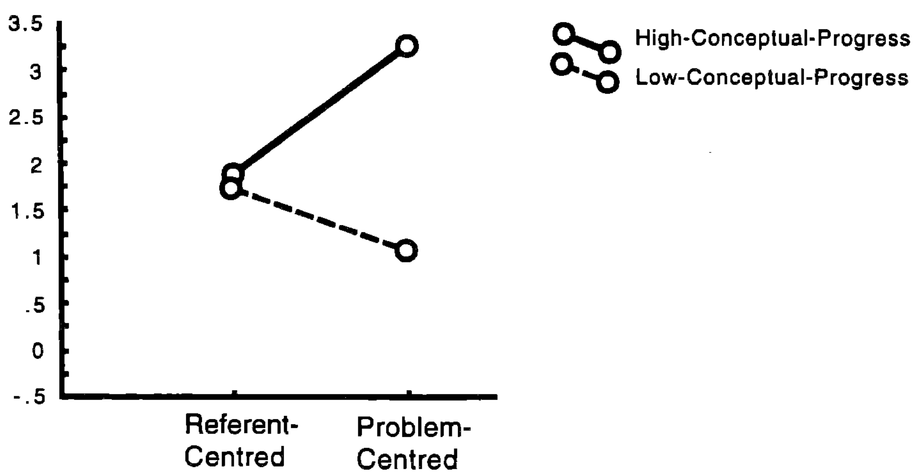

Figure 6. Mean numbers of knowledge items in graphic-medium of CSILE.

of others' knowledge items learners responded, i.e., coordinating or commenting. Here, we focused on a more demographic variable, i.e., how many items they retrieved. The analysis of the variable was carried out to examine if differences in accessing and responding others' knowledge items between the groups of learners were related to differences in numbers of knowledge items they operationally retrieved.

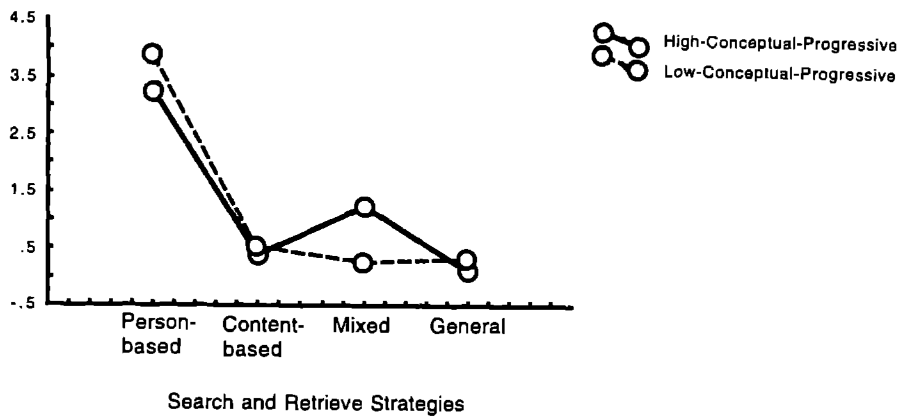

Figure 7. Mean frequencies of sessions in which learners used different search strategies.

Search strategies. Search strategies were examined between the two groups of learners. Each session of search was categorized into one of: (1) person-based search, (2) content-based search, (3) mixed search, and (4) general search. Person-based search meant that a learner searched the database based on names of note authors. Content-based search meant that a learner searched the database based on keywords which were attached with notes, vocabularies in notes, and/or thinking types. The mixed search meant that a learner combined the person-based and the content-based search. The general search meant that a learner searched based on a topic. Topic usually meant the name of assigned by the teacher to a whole unit (e.g., electricity). Thus, a general search would retrieve all the notes by all students for a particular curriculum unit.

A 2 (Type of Learners) × 4 (Type of Search) ANOVA on frequency of the search strategies was carried out. Results showed a significant main effect of Type of Search, $F(3,81) = 15.2$ $p < 0.05$. LSD tests following that showed that both types of learners significantly more often used person-based search than other search strategies (Figure 7).

Number of retrieved knowledge items. To examine differences in numbers of retrieved knowledge items, a 2 (Type of Learners) × 3 (Type of Retrieved Knowledge) ANOVA on number of knowledge items was carried out. Results showed a main effect of Type of Retrieved Knowledge, $F(2,54) = 6.2, p < 0.05$. LSD tests showed that both types of learners retrieved referent-centred knowledge significantly more than problem-centred and metacognitive knowledge in the database, and that they retrieved metacognitive knowledge significantly more than problem-centred knowledge (Figure 8).

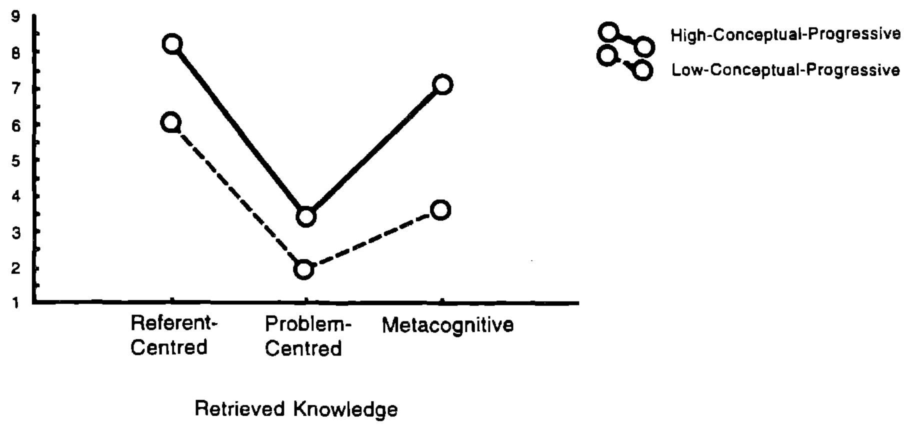

Figure 8. Mean frequencies of knowledge items retrieved by learners.

Summary of differences in computer operations between high- and low-conceptual-progress learners

Although high- and low-conceptual-progress learners manifested different cognitive actions, there were not so remarkable differences in computer operations to attain their different goals in CSILE. However, we could find two noticeable results in the analyses. The first one was the difference in numbers of knowledge items represented in a single note. High-conceptual-progress learners were found to represent more knowledge items in a note than did low-conceptual-progress learners. This result supports the interpretation that they were trying to coordinate knowledge whereas low-conceptual-progress learners were accumulating fragmented knowledge. Furthermore, the result can be interpreted in the following way from the perspective of tool-mediated activity or learner-CSILE interaction. The result suggests a possibility that high-conceptual-progress learners brought more organized knowledge items in CSILE, whereas low-conceptual-progress ones brought very fragmented knowledge item. High-conceptual-progress learners might prepare some modules of knowledge items before using the system. Then they might organize the modules of knowledge items in the database. Thus, high-conceptual-progress learners might recognize CSILE as a higher level of constructive arena for their small organized knowledge.

The second finding worthwhile discussing here is the result that high-conceptual-progress learners were more likely to use graphic-medium to represent their problem-centred knowledge. This result is consistent with results in previous research on mental models (Gentner & Stevens, 1983). High-conceptual-progress learners used more mental models represented in CSILE to advance their explanatory discourses on scientific phenomena. From the perspective of a distributed cognitive system in CSILE, the following possibilities should be examined further. As the research on mental models suggests (e.g., Gentner & Stevens, 1983), the difference between the two groups of learners is considered that high-conceptual-progress learners had mental models but low-conceptual-progress ones did not. More specifically, an important point should be that high-conceptual-progress learners' mental models were represented in graphics as runnable ones whereas were not low-conceptual-progress ones' (Nathan, Kintsch & Young, 1992). This suggests two possibilities. First, we have to consider a possibility that low-conceptual-progress learners did not have ability to make their mental models runnable. Graphics themselves were static images of scientific mechanisms. In order to make their mental models runnable, they needed to annotate some text discourses of and/or show diagrammatically how it works. Second, generally, it could be hard for low-conceptual-progress learners to draw graphics in the medium. They had to use a normal mouse to draw graphics. If you want to create very sensitive graphics, it is quite hard even for us to draw graphics by a mouse. These possibilities should be examined with development of the system itself in the future.

Conclusion

Students who made substantial conceptual progress through collaborative learning activity in the CSILE unit on electricity differed from others at both the action and the operation levels of learning activity (Leontiev, 1981), as examined on both the solo and the joint plane of activity. They made relatively more use of problem-centered than referent-centered knowledge and they tended to make knowledge-deepening rather than knowledge-widening links between items of knowledge, whether in their own work or in work done in interaction with others. These findings are by no means surprising, and so the contribution of the study is not to be sought in empirical or theoretical generalizations that might be drawn from it. Rather, we suggest, the value of the study resides in having articulated a set of collaborative learning process variables that are demonstrably relevant to high-level educational objectives and that can be extracted from discourse protocols.

Although the analyses took advantage of CSILE's resources as a discourse medium, most analyses at the action level could be carried out on transcripts of many kinds of collaborative learning discourse, whether written or oral. Most evaluations of approaches to learning, including previous analyses involving CSILE, have looked at mean effects. The tacit assumption is that all students are engaged in the learning approach in the intended way, so that individual differences in outcomes are due to other factors. Yet, as the present study shows, students may differ quite significantly at the level of cognitive actions, in terms of the goals they are pursuing through the learning activity, even when they are behaving in much the same way at the level of operations.

The distinctions made here between problem-centred and referent-centred knowledge and between knowledge-widening and knowledge-deepening actions are shown to be relevant to students' conceptual progress. These are not good-bad distinctions, it must be emphasized. All combinations of them have a place in building knowledge. But it seems important to know which of these are going on and which may be under-represented in learning situations. Reciprocal teaching, for instance (Brown & Palincsar, 1989), is a collaborative approach to learning from texts that has been demonstrated to have strong effects on students' reading comprehension. Because its focus is on segment-by-segment comprehension, however, dealing with local rather than global questions and clarifications, it is possible that discourse analysis would show a preponderance of knowledge-widening rather than knowledge-deepening actions – or that substantial teacher modeling might be required to bring about the latter. The jigsaw collaborative learning structure (Brown & Campione, 1994) might emphasize one process or the other, depending on how it is handled and on students' motives. This is a structure in which different groups of students acquire different specialized knowledge and then groups are reconstituted so that each student teaches his or her specialized knowledge to the other group members. The first phase, thus, suggests a knowledge-deepening approach, followed in the second phase by knowledge-widening, as students share their separate bodies of specialized knowledge. But it is possible that in some cases or for some students knowledge-widening would predominate in both phases or – more ideally, that both phases would include significant amounts of both. The kinds of analyses used in the present study would make it possible to monitor actions in these and other collaborative learning structures when experimenting with ways to optimize them.

That is the practical application we are trying to make of these analyses in further development of CSILE. In work in progress by the first author, changes in the design of CSILE activity in subsequent years are being assessed using the same kind of analysis. Preliminary results indicate increases in the proportion of problem-centered as compared to referent-centered knowledge items and in the frequency of knowledge-deepening connections.

Acknowledgment

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Appendix A

An example of learner's discourse in CSILE

Student's Written Discourse in CSILE Notes

How I Think Electricity Works

* * *

(1) I think electricity works like this: If you had electricity inside you and you wanted to give your friend some electricity so that they would have the same power as you did, you would use a wire or something that would take the power through it and would take it to the other side.

(2) You would hook one side of it to you and the other side to your friend, then your power would go and meet your friend would have it too.

(3) Another example is: You have two friends.

(4) They don't know each other.

(5) You bring them together, they meet

(6) Now they each have each other as friends like you had them.

- -

Chart 1

- -

HIGH-LEVEL QUESTIONS

WHAT I DON'T UNDERSTAND . . .

(1) 1-How do batteries get their electricity?

(2) 2-What is inside a battery?

(4) 3-Does a light bulb have some of its own electricity or does it get ALL of its electricity from a battery?

(4) 4-When were batteries first used?

- -

How I Think Electricity Works

(1) I think electricity works like this: If you had electricity inside you and you wanted to give your friend some electricity so that they would have the same power as you did, you would use a wire or something that would take the power through it and would take it to the other side.

(2) You would hook one side of it to you and the other side to your friend, then your power would go and meet your friend, so than your friend would have it too.

(3) Another example is: You have two friends.

They don't know each other.

(4) You bring them together, they meet

(5) Now they each have each other as friends like you had them.

- -

(continued to the end of learning)

Appendix B

An example of learner's joint activity

Learner's Search Strategies	Accessed Notes
⟨First Session⟩	
Search notes by author 26119 and topic Electricity	
	2167
⟨Second Session⟩	
Search notes by author 427 and topic Electricity	
	2300
	2234
	2158
⟨Third Session⟩	
Search notes in texts and topic Electricity	
	2381
	2355
	2169
Search notes in texts and graphics, by keyword electricity and topic Electricity	
⟨Fourth Session⟩	
Search notes by author 26119 but not Published	
	2414
(Continued to sixth session)	

References

Bereiter, C. (1992). Referent-centred and problem-centred knowledge: Elements of an educational epistemology. *Interchange* 23(4): 337–361.

Brown, A. L. & Campione, J. C. (1994). Guided discovery in a community of learners, in K. McGilly, ed., *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice*. Cambridge, MA: MIT Press/Bradford Books.

Brown, A. L. & Palincsar, A. S. (1989). Guided, cooperative learning and individual knowledge acquisition, in L. Resnick, ed., *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser* (pp. 393–451). Hillsdale, NJ: Lawrence Erlbaum Associates.

Brown, J. S., Collins, A. & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher* 18: 32–48.

Cicourel, A. V. (1990). The integration of distributed knowledge in collaborative medical diagnosis, in J. Galegher & R. E. Kraut, eds., *Intellectual Teamwork: Social and Technological Foundations of Cooperative Work* (pp. 221–242). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cohen, A. (1994, April). The effect of the intrapsychological plane on the activity of learning in a CSILE classroom, in G. Wells (Chair). *Activity and Discourse in the Classroom.* Symposium in the annual meeting of the American Educational Research Association, New Orleans.

Collins, A., Brown, J. S. & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics, in L. B. Resnick, ed., *Knowing Learning, and Instruction: Essays in Honor of Robert Glaser* (pp. 453–494). Hillsdale, NJ: Lawrence Erlbaum Associates.

Galegher, J., Kraut, R. E. & Egido, C., eds. (1990). *Intellectual Teamwork: Social and Sociological Foundations of Cooperative Work.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Gentner, D. & Stevens, A. L., eds. *Mental Models.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Hutchins, E. (1990). The technology of team navigation, in J. Galegher, R. E. Kraut & C. Egido, eds., *Intellectual Teamwork: Social and Sociological Foundations of Cooperative Work* (pp. 191–220). Hillsdale, NJ: Lawrence Erlbaum Associates.

Leontiev, A. N. (1981). The problem of activity in psychology, in J. V. Wertsch, ed., *The Concept of Activity in Soviet Psychology.* Armonk, NY: Sharpe.

Lotman, Y. M. (1988). Text within a text. *Soviet Psychology* 26(3): 32–51.

Nathan, M. J., Kintsch, W. & Young, E. (1992). A theory of algebra-word-problem comprehension and its implications for the design of learning environments. *Cognitive and Instruction* 9(4): 329–389.

Norman, D. A. (in press). Cognitive artifacts, in J. M. Carroll, ed., *Theory and Design in Human-Computer Interaction.*

Oshima, J. (1994, April). Coordination of solo- and joint-plane of cooperative work in CSILE, in G. Wells (Chair), *Activity and Discourse in the Classroom.* Symposium in the annual meeting of the American Educational Research Association, New Orleans.

Pea, R. D. & Gomez, L. M. (1992). Distributed multimedia learning environment: Why and how? *Interactive Learning Environments* 2(2): 73–109.

Salomon, G., ed. (1993). *Distributed Cognitions: Psychological and Educational Considerations.* Cambridge, MA: Cambridge University Press.

Salomon, G., Perkins, D. N. & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Research* 20(3): 2–9.

Scardamalia, M. & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *The Journal of the Learning Sciences* 1(1): 37–68.

Scardamalia, M. & Bereiter, C. (1994) Computer support for knowledge-building communities. *The Journal of the Learning Sciences.*

Scardamalia, M. Bereiter, C., Brett, C., Burtis, P. J. Calhoun, C. & Smith-Lea, N. (1992). Educational applications of a networked communal database. *Interactive Learning Environments* 2(1): 45–71.

Scardamalia, M., Bereiter, C., McLean, R. S. Swallow, J. & Woodruff, E. (1989). Computer-supported intentional learning environments. *Journal of Educational Computing Research* 5(1): 51–68.

Wells, G. (1994, April) Discourse as tool in the activity of learning and teaching, in G. Wells (Chair), *Activity and Discourse in the Classroom.* Symposium in the annual meeting of the American Educational Research Association, New Orleans.

Wertsch, J. V. (1991). *Voices of the Mind: A Sociocultural Approach to Mediated Action.* Cambridge, MA: Harvard University Press.

Wertsch, J. V., Minick, N. & Arns, F. J. (1984). The creation of context in joint problem-solving, in B. Rogoff & J. Lave, eds., *Everyday Cognition: Its Development in Social Context* (pp. 151–171). Cambridge, MA: Harvard University Press.

Winograd, T. & Flores, F. (1986). *Understanding Computers and Cognition: A New Foundation for Design*. Norwood, NJ: Ablex.