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VISUAL REPRESENTATION OF A MULTIDIMENSIONAL CODING SCHEME FOR UNDERSTANDING TECHNOLOGY-MEDIATED LEARNING ABOUT COMPLEX NATURAL SYSTEMS

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Understanding how people learn requires that we consider how moments fit together: the actions learners take, the conversations they engage in, and the representations that they use. The goal of this article is to describe a data visualization technique in the context of a specific research project involving a computer-supported complex system modeling environment. The goal of this project was to understand the relationship between the students' epistemic practices of science inquiry, collaborative processes, and the content of what they were learning as indicated by their structure-behavior-function reasoning. To accomplish this research goal, we used the Chronologically-oriented Representation for Discourse and Tool-related activity (CORDTRA diagrams) technique to conduct a contrasting case analysis. The discourse of two groups was coded for collaborative activity, epistemic practices, and the mention of structures, behaviors, and functions. These three coding schemes were juxtaposed on a single timeline in a CORDTRA diagram. The analysis of the CORDTRA diagrams provided some suggestions for how different patterns of activities may be more or less indicative of productive engagement. This case study provides an example of CORDTRA in use, but it can be used more generally to integrate across multiple sources of data and multiple coding schemes as well as allowing researchers to study sequential activity at both large and small grain sizes. We argue that, in comparison to other techniques, this kind of representation can be a powerful way of understanding complex technology-mediated learning environments.

Keywords: Representation; complex system; collaborative learning; epistemic practice.

> A heartbeat, a breath, a step, a spoken word takes but a moment; a stroll, a conversation, extends over many such moments... And yet a conversation consists of many momentary utterances...
> (Lemke, 2000, p. 273)

Understanding how people learn requires that we consider how these moments fit together: the actions learners take, the conversations they engage in, and the representations that they use. This is especially important in technology-mediated learning environments. Such environments are complex contexts for learning and often require integrating across multiple kinds of data and across multiple coding schemes. Often such data are represented as frequencies of discourse acts, content references, or logs of tool use. Such representations, however, can obscure the relation between different codes as well as hide sequential information. Here, we describe a specialized technique for visually representing multiple coded data through time and compare this technique to other traditional approaches. To do so, we use the context of group work with simulations as part of the RepTools toolkit to learn about a model natural system (Hmelo-Silver, Liu, Gray, Finkelstein, & Schwartz, 2007). The instructional approach organizes the content around structure-behavior-function reasoning as middle school students engage in collaborative inquiry practices. We describe data from two groups selected on the basis of classroom performance. One group was highly successful and the other less so.

This work is situated in a social constructivist framework, which posits that learning is mediated by tools (Cole & Engeström, 1993) and that knowledge is socially constructed (Palincsar, 1998). This perspective argues that to understand learning in context, it is critical to understand how tools and social activity are part and parcel of the learning process. This understanding necessitates examining how discourse unfolds over time.

Many approaches to studying discourse involve coding and counting and creating static snapshots of learning using intricate multilevel coding schemes (e.g. Chinn & Anderson, 1998; Engle & Conant, 2002; Hmelo-Silver, 2003; Hmelo-Silver & Barrows, 2008) whereas other researchers have used more qualitative approaches to studying collaboration, such as Roschelle's (1992) study of computer-mediated convergent collaborative conceptual change. The latter provides a detailed look at portions of a collaborative process, focusing on social and linguistic processes. Some of the former approaches blend reliable cognitive and social analyses over larger periods of time but lose the chronological detail and often, the relation between different kinds of utterances.

We, however, are interested in both how the different aspects of discourse relate to each other over time as well as how the discourse relates to the tools being used in the collaborative learning process. This entails gaining an understanding of how collaborations unfold and how tools are used, and therefore going beyond coding of individual speech acts to a consideration of longer sequences of speech. Lemke (2000) argues that to understand sociotechnical systems, researchers need to understand processes involved, who and what is participating, and how these are related to each other. This suggests that researchers should consider the chronological dimension of learning (Chiu, 2008; Mercer, 2008; Reimann, 2007). We believe visual representations can be important tools for helping researchers make sense of complex multidimensional data. In this article, we discuss a specific technique for analyzing such data, which enables us to detect chronological patterns in collaborative discourse, and how those patterns may be mediated by technological tools.

1. Visual Representations for Understanding Complex Learning

Trying to understand the complexity of technology-supported learning environments is a complicated undertaking that often requires the use of multiple data sources. As Larkin and Simon (1987) noted, a diagram is often much easier to interpret than verbal presentations of the same material. For example, directed graphs have been used to map the semantic space of instructional discourse as students coordinated conceptual and procedural knowledge (Strom, Kemeny, Lehrer, & Forman, 2001). In another example, Martinez, Dimitriadis, Rubis, Gomez, and de la Fuente (2003) analyzed Computer Supported Collaborative Learning (CSCL) data using quantitative measures, social network analysis, and qualitative data. Even though the sociogram showed interaction patterns, it was not easily integrated with other sources of data such as the semantic content of the interactions.

Similarly, sequential data analysis provides a statistical approach to analyzing discourse (Erkens, Prangsma, & Jaspers, 2006; Jeong, 2003). This technique provides information and diagrams about the probability of a particular discourse move following another and creates graphical representations that show the degree of probability in terms of the thickness of lines between different discourse moves. This has the advantage of quantifying the relation between discourse moves but the disadvantage of being limited to only a short sequence. For example in Jeong (2003), it was used to examine only pairs of discourse moves. This is useful in some research contexts but may be limited in detecting patterns over longer timescales.

Another approach involves constructing diagrams to show how ideas are taken up in a CSCL group (Suthers, Dwyer, Medina, & Vatrapu, 2009). In addition to this uptake analysis, inquiry threads can enable an understanding on how ideas emerge over time (Zhang, Scardamalia, Messina, & Reeve, 2007). This approach shows how the content of threads in an online database is engaged over time. Both this approach and the uptake analysis technique trace ideas over time in CSCL environments but may not necessarily integrate other kinds of discourse codes or forms of data.

In order to integrate both discourse codes and logs of student navigational activity, Luckin (2003) developed the CORDFU (Chronologically-oriented Representation of Discourse and Features Used) methodology to study children collaborating around multimedia. Luckin and colleagues used this approach to examine how alternative ways of structuring hypermedia affected collaborative discourse, allowing them to explore relations between the software's features and collaborative knowledge construction. In all these cases, the investigators needed to make sense of multiple sources of data or complex learning environments.

Visual representations can be used at different timescales to achieve different goals. Visualizations at a macro level can show activities that have been sustained over long time periods. This whole picture can then be used to contextualize, structure/organize, and focus on micro analyses of idea development and discourse patterns to understand trajectories of knowledge and activities.[1] Sequential data analysis and uptake analysis clearly focus on the micro-level. Zhang *et al.*'s (2007) analysis of inquiry threads is at a macro-level of analysis. We argue that the CORDFU technique (and our CORDTRA adaptation) is at an intermediate level of analysis, as it can allow an examination of discourse and tools over a somewhat extended period of time (hours to days) but it also supports the micro-level of analysis.

Here we describe the Chronologically-ordered Representation for Tool-Related Activity (CORDTRA) as a means to study multiple aspects of coded discourse over time. This technique is a generalization of the CORDFU methodology (Luckin, 2003; Luckin *et al.*, 2001). Our work considers the relation of tools and discourse, broadly construed. CORDTRA diagrams contain a single timelines that allow a researcher to juxtapose a variety of codes to understand an activity system — for example, these might be discourse, gestural, or tool-related codes. The specifics of the codes or computer logs chosen will depend on the research questions being asked. Initially, we used this technique to examine face-to-face collaboration in a problem-based learning (PBL) tutorial to understand how constructing a representation mediated learning (Hmelo-Silver, 2003). In this work, a multilevel coding scheme was used to code discourse at a fine grain of analysis (the conversational turn) to capture different features of the discourse. These were used to compile frequency counts and to get a sense of how the PBL tutorial unfolded. This technique was also used to examine an online CSCL environment for preservice teachers as it juxtaposed log data and discourse codes (Hmelo-Silver, Chernobilsky, & Jordan, 2008; Hmelo-Silver, Nagarajan, & Chernobilsky, 2009). These applications of CORDTRA demonstrated the differences between strategies used by more and less effective groups with regard to the kinds of talk they engaged in and how they used the tools (Hmelo-Silver *et al.*, 2008). They also demonstrated how these strategies changed over time as students became more familiar with both the tools and PBL activity structure. In these earlier applications of CORDTRA, the students were adults working either in a face-to-face collaboration or online.

In this article, we examine applying CORDTRA to younger learners who are working together face-to-face with computer simulations. Given the methodological focus of this special issue, we will first explain how to create and use the CORDTRA diagram before launching into the case study.

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[1] We thank an anonymous reviewer for pointing this out.

2. Creating and Using the CORDTRA Diagram

The CORDTRA diagrams are created using a commercial spreadsheet program, Microsoft Excel. Multiple forms of data can be represented as codes. In the case study presented here, we use three sets of discourse codes related to collaboration, epistemic practices, and the science content. In other studies, we have used computer log data as well as other discourse codes and gestures (Hmelo-Silver, 2003; Hmelo-Silver *et al.*, 2008, 2009). Typically, we represent each discourse code, gesture type, or log data as a single column in the spreadsheet and represent each code numerically. This allows us to create a simple scatterplot using Excel's built in graphing capabilities. Because each coding or log category is represented as a number on the y-axis, each occurrence of that code is represented as a symbol at the appropriate turn, represented on the y-axis.

The initial foray into using CORDTRA involved exporting the codes from qualitative data analysis software, which serendipitously had a limit of 26 codes that could be exported into Excel (Hmelo-Silver, 2003). This analysis of a problem-based learning tutorial focused on an episode in which students were drawing an informal concept map as they were constructing explanations of a patient problem. This was a face-to-face tutorial group and the CORDTRA diagram included discourse codes, gestures, and drawing activity. This meant that researchers needed to carefully consider the codes displayed in relation to research questions. In a subsequent attempt at using CORDTRA, we coded directly in Excel resulting in 80+ coding categories. We found the diagram generated from these codes to be nearly uninterpretable (Chernobilsky, Hmelo-Silver, & DelMarcelle, 2003). Codes used in this analysis included computer log data, discourse content and computer log events. Based on our experience with this impractical diagram, we advise using far fewer coding categories.

In interpreting the CORDTRA, we recommend a two-step process. First, it is helpful to begin with the broad view. Without even looking at the code key to see what different symbols represent, it is useful to hold the diagram at a distance and look for any obvious patterns or natural divisions in the symbols. In the analysis of the drawing episode in Hmelo-Silver (2003), this broad view made it clear that there were three distinct parts of the activity which sent the researchers back to inspect the transcripts. This inspection led to the rapid identification of three phases. The middle phase was of particular interest and the researcher could then zoom into that part of the diagram to see what was happening at that process.

After the broad inspection, the researcher would then orient to how the symbols are arranged and what they represent. Using the previous example, in the middle phase, the diagram showed that as students switched levels of the content that they were drawing, they were generating causal explanations near each of these time points. Thus, by zooming in on the diagrams, the researchers could see how different events were related to each other.

In the case study that we present in the next section, our goal was to study the relation between collaborative acts, epistemic practices of science, and the how this was related to the content that young learners talked about. We represent the collaboration, epistemic practices, and the science content codes chronologically in the CORDTRA graphs. The horizontal axis represents turn number. The vertical axis represents the categories of the three different coding schemes. That is, each turn of discourse can have one symbol for a code in each of the collaboration, epistemic practices, and science content categories. The CORDTRA graphs, therefore, make it possible to visualize the patterns of collaboration and epistemic practices, the relations between the features of collaboration and epistemic practices, and how the patterns are related to the science content about which the group was discussing.

The data for this study are a sample drawn from Liu (2008). In this research, we present a contrasting case analysis that allows us to compare groups that are more and less successful. Examination of distinctly dissimilar cases can exploit the variability among cases and thus facilitate discovery of appropriate explanations and hypothesis generation (Firestone, 1993).

3. A CORDTRA Case Study: RepTools Context

Although our focus is on the CORDTRA technique, we situate the analysis in an effort to understand how students learn about complex natural systems through using simulations that are part of the RepTools project (Hmelo-Silver *et al.*, 2007). The RepTools suite includes computer-based representational tools for inquiry into complex biological systems. The design of our instructional intervention was informed by structure-behavior-function (SBF) theory, which originated in artificial intelligence research (Goel *et al.*, 1996). Given that our science content focused on processes within a living aquarium, we provide aquaria related examples. Structures refer to components of a system (e.g. fish, plants, filter, water). Behaviors refer to how the structures of a system achieve their output. These are the interactions or mechanisms that yield a product, reaction, or outcome (e.g. bacteria remove waste by converting ammonia into harmless chemicals). Finally, functions refer to the role or output of an element of the system (e.g. lights provide energy). SBF theory suggests that by considering structures, behaviors, and functions, one can reason effectively about complex systems, and indeed, in the domain of instruction, experts reason in ways consistent with SBF theory (Hmelo-Silver, Marathe, & Liu, 2007). The RepTools toolkit includes a function-oriented hypermedia and two NetLogo computer simulation models (Wilensky & Reisman, 2006).

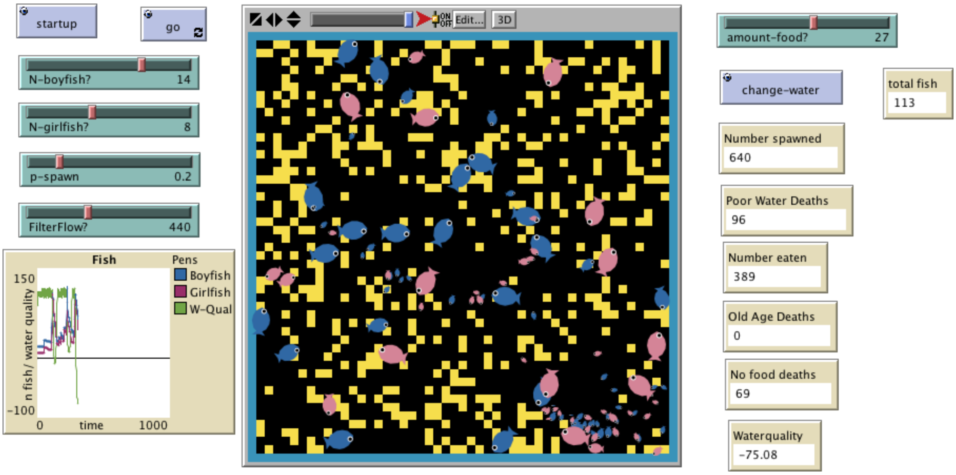
In the context of this study, the hypermedia introduces the aquarium system with a focus on the functional aspects but provides linkages between the structural, behavioral, and functional levels of aquariums, as shown in Figure 1 (Liu & Hmelo-Silver, in press). By exploring this hypermedia, students can construct a basic understanding of the system to prepare them for their inquiry activities with the simulations. The hypermedia can also be available as a reference to help students interpret the simulations. The function-oriented hypermedia introduces students to this system with two broad functional and behavioral questions on the

Aquarium:
An Ecosystem

Why is it necessary to maintain a healthy aquarium?

Why do fish and other living things have different roles in the aquarium?

Figure 1. Aquarium hypermedia.



N-boyfish? 14
N-girlfish? 8
p-spawn 0.2
FilterFlow? 440
amount-food? 27
total fish 113
Number spawned 640
Poor Water Deaths 96
Number eaten 389
Old Age Deaths 0
No food deaths 69
Waterquality -75.08

Figure 2. NetLogo simulation.

opening screen: “Why is it necessary to maintain a healthy aquarium?” and “Why do fish and other living things have different roles in the aquarium?” By clicking on these questions, the students can go to information about the functional aspects of the system, then to the behavioral aspects and finally to the structural information.

We also use two NetLogo simulations — the fish spawn model and the nitrification process model (Figure 2) — presenting models of aquaria at different scales. The fish spawn model simulates macrolevel changes in population density as fish spawn within the aquarium. The purpose of the model is to help students learn about the relationships among different aspects of an aquarium ecosystem, such as the amount of food, initial gender ratio, filtration, water quality, reproduction, and fish population dynamics. The nitrification process simulation presents a microlevel model of how chemicals reach a balance to maintain a healthy aquarium. This simulation allows students to examine the bacterial-chemical interactions that are critical for maintaining a healthy aquarium. In both NetLogo simulations, students can adjust the values of variables such as fish, plants, and food with sliders. Figure 2 shows an example screen from the fish spawn simulation. Counters and graphs provide alternative representations for students to examine the results of their inquiry. Students can observe the simulations, generate hypotheses, test them by running the simulation and modify their ideas based on observed results.

As students work with the RepTools materials, they have demonstrated substantial learning gains on pre and post tests (Hmelo-Silver, Liu, Gray, Finkelstein, & Schwartz, 2007; Liu, 2008). Although those results demonstrated that students do indeed learn about aquaria, we wanted to better understand how they learned by examining the relationship between collaborative learning processes, epistemic practices, and content understanding.

One way to examine this would be to code and count these different activities, but to understand the temporal processes involved (Hmelo-Silver, Liu *et al.*, 2007), the CORDTRA analysis is necessary. In our results, we examine what we learn from simple frequency counts and we then examine what the additional temporal dimension adds with the CORDTRA diagrams.

4. Methods

4.1. *Participants*

The data for this research was drawn from a larger study by Liu (2008). The participants in the larger study were 145 middle school students from two public schools who volunteered to participate in this study. Seventy were seventh graders taught by Ms. W. Seventy five were eighth graders taught by Mr. K. Their teachers randomly assigned these students into groups and twenty focal groups' interactions were video and audiotaped. The study was conducted in seventh and eighth grades as part of students' science instruction. In this analysis, we contrast two of these focal groups, a high achieving group from Mr. K's class and a low achieving group from Ms. W's class. We selected these groups because although they were both engaged and began with similar pretest scores, posttest scores indicated that one group (group 8) demonstrated considerable conceptual growth and the other (group 14) did not (see Liu, 2008 for details). Although these groups have some important differences such as different instructors, we selected two groups that would provide maximal contrast for our illustration of how CORDTRA can be used.

4.2. *Instructional context*

Both teachers used the unit for approximately two weeks (ten 40-minute class periods) and succeeded in getting students engaged in most of the learning events.

In both classrooms, before using the computer simulations, both teachers started with a class discussion on the aquarium ecosystem to activate students' prior knowledge and make connections to the physical fish tank in the classrooms. Then the teachers introduced the hypermedia. Students explored the hypermedia software in groups followed by other activities such as class discussions and construction of concept maps that connected parts of the system to their function. Students then collaboratively explored the fish spawn and nitrification process simulations. Although there was some variability between the two teachers and for each teacher, across their five classes, students generally worked with each of the two simulations for one to two class periods.

4.3. *Data analysis*

The video and audiotapes of the groups' discourse throughout their exploration of the computer simulations were transcribed verbatim. The discourse was segmented and coded by conversational turns (i.e. changes in the speaker). Three sets of codes were developed and applied to investigate students' collaborative learning through different lenses: collaborative discourse, epistemic practices, and the content related to the student's learning goals (i.e. regarding the content: the structures, behaviors, and functions [SBF] in the system).

Collaborative discourse and epistemic practices are closely related activities in learning science. Engaging in collaborative discourse provides a rich environment for mutual discovery, reciprocal feedback, and frequent sharing of ideas (Damon & Phelps, 1989). However, collaborative discourse is not always productive: students may not see science as a process of conducting experiments to test ideas (Carey & Smith, 1993; Dillenbourg, 1999; Sandoval & Reiser, 2004). In other words, whether collaborative discourse is productive might be related to students' epistemological knowledge about science. In our study, we regard epistemic practices as the cognitive and discursive activities that students engage in to demonstrate their epistemological knowledge of the nature of science. By coding both students' collaborative discourse and epistemic practices, we aim to further investigate the reciprocal relations between these two kinds of engagement. We hypothesize that the more sophisticated epistemic practices may lead to better quality of collaborative discourse. We agree with Kuhn's view that a great many students engage in science learning activities, such as collaborative communication, without understanding that the activity presents an opportunity to find out something. Thus, they may fail to engage in appropriate epistemic practices and come away with little indeed (Kuhn, 2002).

The *collaborative discourse* coding scheme was designed to uncover cognitive and metacognitive processes underlying the groups' discourse as well as the facilitators' roles (Table 1). There are three major subcategories in the coding scheme: students' cognitive processing, students' metacognitive processing, and teacher's facilitating. All the codes under the first two subcategories were used for students' conversational turns only, and those under the third subcategory were used for teacher's

Table 1. Definitions for collaborative coding categories (Liu, 2008).

Categories	Definitions	Examples
Cognitive Process		
Fact Question	Questions asked with a purpose to obtain factual information	“What is the yellow stuff?”
Explanation Question	Questions asked with a purpose to obtain cause-effect information	“Why is water qualify dropping?”
Confirm Question	Questions asked to make sure one gets the shared information	“The males couldn’t wait to make more fish so they what?”
Directing Statement	Demanding statement for an ongoing activities	“Change the water now.”
Agree	Explicit express of acceptance of other’s ideas	“Okay I guess that makes clear sense.”
Disagree	Expressing express of rejection of other’s ideas	“No. This is not true.”
Share Knowledge	Share information with other members in the group	“I have fish, plants, bacteria1, bacteria2, ammonia, nitrite and nitrate.”
Describe Observation	Descriptions of what is observed in the simulations	“Now there are no more male fish”
Retrieve Prior Knowledge	Making connections to one’s previously perceived knowledge or experiences	“We know that there is bacteria inside the water that eats the bad bacteria.”
Generate Theory	Statement of a hypothetical proposal	“When there were more female fish they ate all the smaller fish and then died.”
Paraphrase	Rewording other’s statements	“Okay so when there were more female fish they ate the smaller fish and died of old age.”
Warranted Claim	Statements to provide ground for an idea	“Well we are looking at the chart and it tells how ammonia, the bacteria turns it into nitrate. Doesn’t it kind of prove that the stuff in the back is bacteria then.”

Table 1. (*Continued*)

Categories	Definitions	Examples
Identify Cognitive Conflict	Realizing the discrepancies in one's or the group's reasoning	"Because the model we have is that when there are more female fish they eat the smaller fish and then they died of old age. But then they are eating the smaller fish and none of them are dying of old age."
Off-Topic Talking	Statement unrelated to the learning target	"Can I borrow your pen?"
Metacognitive Process		
Plan	Defining the learning goals	"Okay we have to figure out what they do."
Monitor	Reflecting on the learning process to keep track of the conceptual understanding	"We haven't explain how they keep a balance?"
Review	Looking back on the strategies (e.g. designing experiments, running simulations) that lead to knowledge construction	"Well we tried to take away the plants . . . and then nothing even happened."
Evaluate	Judging the effectiveness of learning strategies	"Using one fish for each gender helped to find out which gender lives longer."
Facilitators' Roles		
Educational Statement	Statements related to the learning content and strategies	"You need to move on to the next question."
Performance Statement	Statements related to class management and students' performance	"Try to look at the hypermedia. Maybe you will get some information there."
Open Question	Questions seeking an elaborated answer or explanation	"How do you know the water quality has decreased?"
Closed Questions	Questions seeking a short and factual answer	"Are all of those bad for water quality?"

conversational turns. These coding categories are indicative of different aspects of students' cognitive and metacognitive engagement or teacher's scaffolding strategies. For example, different types of questioning (i.e. fact, explanation, confirmation questions) initiate different level of elaboration and thinking. Through sharing knowledge, learners exchange ideas about how they make meaning of the knowledge. The dis/agreement among group members presents the extent of convergence in the collaborative learning. Paraphrasing, warranting claims, describing observations, retrieving prior knowledge each indicate the trajectories of students' inquiry. Identifying cognitive conflict explicitly presents the knowledge disequilibrium during the collaborative knowledge co-construction. Planning, monitoring, reviewing and evaluating are the essential metacognitive strategies that learners apply to guide their thinking and inquiry process. Since the focus of the study is on students' interaction, the facilitators' interactions are coded into four rough categories to indicate the teachers' facilitation moves. Particularly, the educational and performance statements indicate whether the focus of facilitation is on understanding or on tasks. The open and closed questioning indicates how the facilitators scaffold understanding.

The second coding scheme was developed to capture the characteristics of *epistemic practices* (i.e. the practices embodying ways of scientific thinking and how learners work on knowledge construction task, see in Duschl & Osborne, 2002) to build understanding (Table 2). The coding categories present a set of discursive practices for generating and evaluating knowledge. Basic knowledge construction is a low level practice of superficial meaning making without deep mental processing. Exchanging knowledge and giving feedback are common practices during collaborative learning to explicitly articulate knowledge and respond to each other. The coding list also includes other practices common to science inquiry, including predicting, designing experiment, coordinating theory-evidence, modifying knowledge, checking knowledge validity. These categories are essential indicators to show how students construct theories to interpret the computer simulations. Scientists often go through cycles of such practices to modify existing knowledge and construct sophisticated theories and develop epistemological understanding. It is necessary to clarify that the coding for modifying knowledge is not simply changing ideas. Rather it was coded as modifying knowledge only when the learner gave the reasons for such a change. The scaffolding category is used for facilitators' supporting practice only.

The third coding scheme for *SBF content* was developed to capture the extent to which students talked about structures, behaviors, and functions. This allowed us to examine how the students talked about content as they engaged in their exploration of the simulation, particularly in the context of how we had structured the instruction. The instructional intervention was organized to help the students learn to use SBF as a way of thinking about systems. The discourse was coded for structures in statements that are focused on the "what's" of system without anything else, i.e. (figuring out what is what). An example of this is "What is

Table 2. Definitions for epistemic practice coding categories (Liu, 2008).

Categories	Definitions	Examples
Basic Knowledge Construction	Superficial meaning making practice without reasoning or supporting evidence.	“What is the yellow? Yeah, I think is food or is that like dirt?”
Observe	Practices of observing phenomena on the computer screen.	“Wow! Look it, it went down real quick.”
Predict	Practices aiming to propose predicting result of a simulation.	“And if you increase it to 2000 they’ll die more quicker.”
Design Experiment	Designing a simulating experiment to test hypotheses.	“How about we if put this, and this all the way down to zero? And put this thing on the top?”
Check Knowledge Validity	Examine the consistency or accountability of constructed knowledge by taking several experimental trials.	“No, see this number is like the same, whatever this corresponds to this. It’s still 8. Ammonia and saturated in nitrite. But 82 and 75... it adds up to the same number.”
Coordinate Theory-Evidence	Practices entailing using theories to explain data and using data to evaluate theories.	“So the plants absorb nitrite because the yellow disappeared. Nitrite, which... comes from nitrate. Nitrate with an A, nitrate comes from nitrite, nitrite comes from ammonia, from the bacteria, the white went in and went through the patch.”
Modify Knowledge	Making a change in previously constructed knowledge.	“No, the patch is not fish. It is bacteria.”
Exchange Knowledge	Explicit articulation of one’s knowledge to others.	“So you are saying fish excrete ammonia to become nitrite.”
Give Feedback	Providing evaluative responses to other’s statements or actions.	“Yes, you are right. The red dots disappeared.”
Scaffold	Applying purposeful strategies to support other’s understanding (for teacher’s turns only).	“So what does that explain about different kinds of models?”

the red dot?" as students were trying to determine what a simulation object was. Statements were coded as behaviors when they referred to how the system worked — processes, states and transitions. An example of this would be a student saying "the red dots are increasing." Statements were coded as functions if they referred to the roles of particular structures or outputs of different parts of the system. An example function statement is "the fish excrete ammonia."

These coding schemes were both valid and reliable. The construct validity of the coding schemes was achieved by reference to related literature and consultation with experts. Reliability was achieved by training an independent coder who then coded 20% of the 20 focal groups' transcripts for the collaborative discourse coding and epistemic practices. The SBF coding was only used for these two cases and all the data for the two groups were coded by two independent coders for the SBF coding scheme. The interrater reliability was assessed by calculating the percentage of interrater agreement. The interrater agreement for the collaborative discourse coding is 91.76%; the interrater agreement for the epistemic practice coding is 93.33%; and the interrater agreement for SBF was 87%.

5. Results

As described earlier, we contrast two of the focal groups: Group 8 is a high achieving group from Mr. K's class; Group 14 is a low achieving group from Ms. W's class. The learning achievements were demonstrated by pre and posttest gains (Liu, 2008). Overall, group 8 talked more while using the simulations, a total of 518 turns compared with 296 turns for Group 14. To demonstrate the affordances of different visual representations in understanding student interaction in a complex learning environment, we first present frequency counts in the form of histograms and then the CORDTRA diagrams. These are presented as percentages to account for the different numbers of turns in each group.

5.1. *Frequency counts and histograms*

The frequency counts (as percentages) are displayed in Figures 3 and 4. The results showed that compared to the low achieving group (Group 14), the high achieving group (Group 8) made more efforts to describe their observations, paraphrase, ask explanation questions and propose warranted claims. In addition, this group seemed more likely to respond directly to each other's ideas as shown by both the number of agreements and disagreements but we do not have a sense of how this process unfolded dynamically. The low achieving group asked more fact questions and were more likely to issue directing statements that sent other group members to the next steps without negotiation. Based on the nature of the students' questions and negotiations, the students in the high achieving group appeared to be engaged in deeper processing than students in the low achieving group.

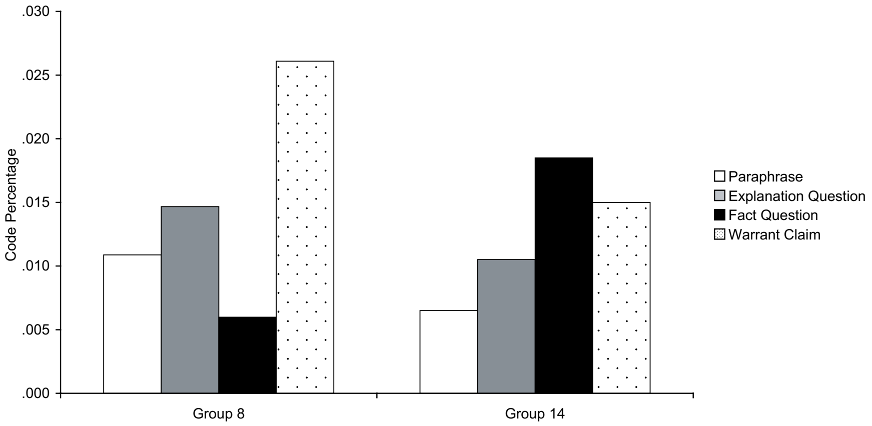


Figure 3. Collaboration frequencies.

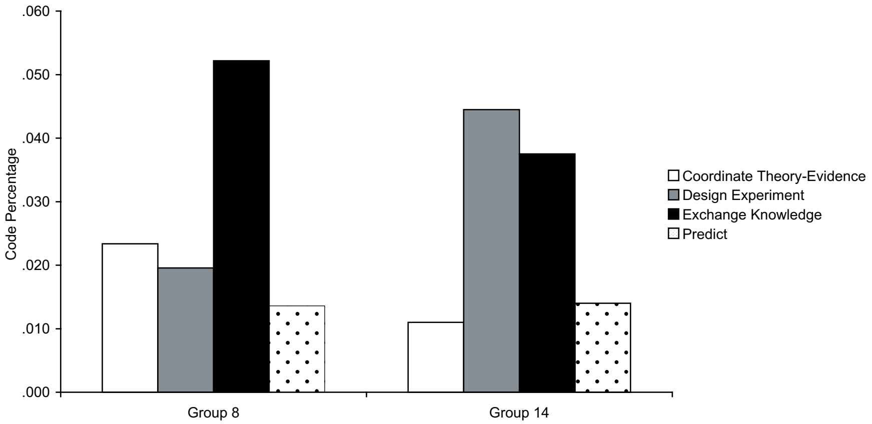


Figure 4. Epistemic practices frequencies.

With respect to SBF content, we also noted differences between groups. When inspecting the SBF frequencies (Fig. 5), the high achieving group appears to talk more about function than the low achieving group, which was more likely to talk about structure and behavior. Although the students in both groups were talking about behavior and function as they explored the simulations, which are associated with deep understanding and not often seen in learners of this age (Hmelo-Silver *et al.*, 2007), the low achieving group talked more about behaviors than the high achieving group, a result that we found a bit puzzling. By looking at isolated frequencies in terms of behaviors and functions we found it difficult to understand how the collaborative processes, epistemic practices, and discussion of content were related both within a particular coding scheme and across coding schemes.

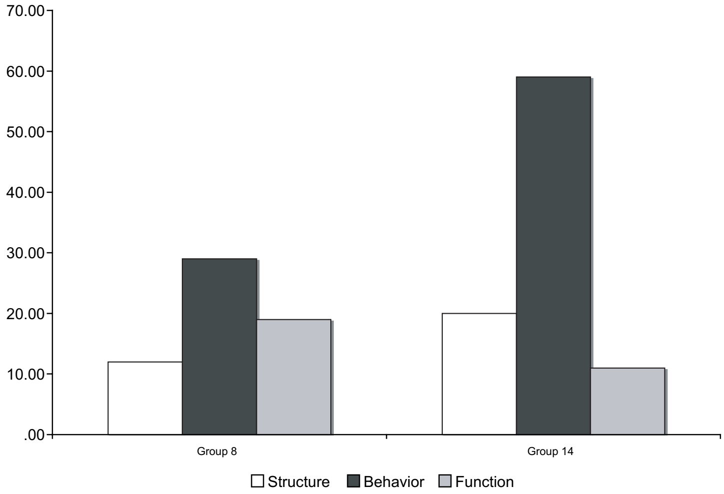


Figure 5. SBF frequencies.

5.2. ***CORDTRA analyses***

5.2.1. *Overview*

To understand how students' discourse unfolded, we delve more deeply into the CORDTRA diagrams in Figures 6 and 7. In particular, these diagrams focus on one of the more difficult pieces of the task — student discourse as they tried to make sense of the nitrification process while working with the microlevel NetLogo simulation. The horizontal axis in the CORDTRA diagram represents turn number, which is a rough approximation of time. The vertical axis represents the different coding categories indicated by the legend on the right.

We started our analysis using the CORDTRA diagrams with a broad overview of the full diagrams held at a distance. This big picture look began by just looking at the overall patterns without attending to the legend for any specifics. The first obvious difference was in the overall amount of talk, with the high achieving group (Figure 6) having more conversational turns than the low achieving group (Figure 7). A glance at the high achieving group suggested that they had 3–4 distinct phases of activity: an initial portion dominated by sharing knowledge and warranting claims, a middle portion that involved a great deal of observation, and then (starting around turn 400) open ended questioning and knowledge exchange and ended with continued work with the simulation and focus on function. The low achieving group looked quite different, and their phases were almost the opposite of the high achieving groups. These students jumped right into exploring the simulation and describing their observations, then in a second phase, starting near turn 50, engaged in knowledge exchange and theory generation, and then by around turn 225, a third phase began that focused on working with the simulation and talking about behaviors.

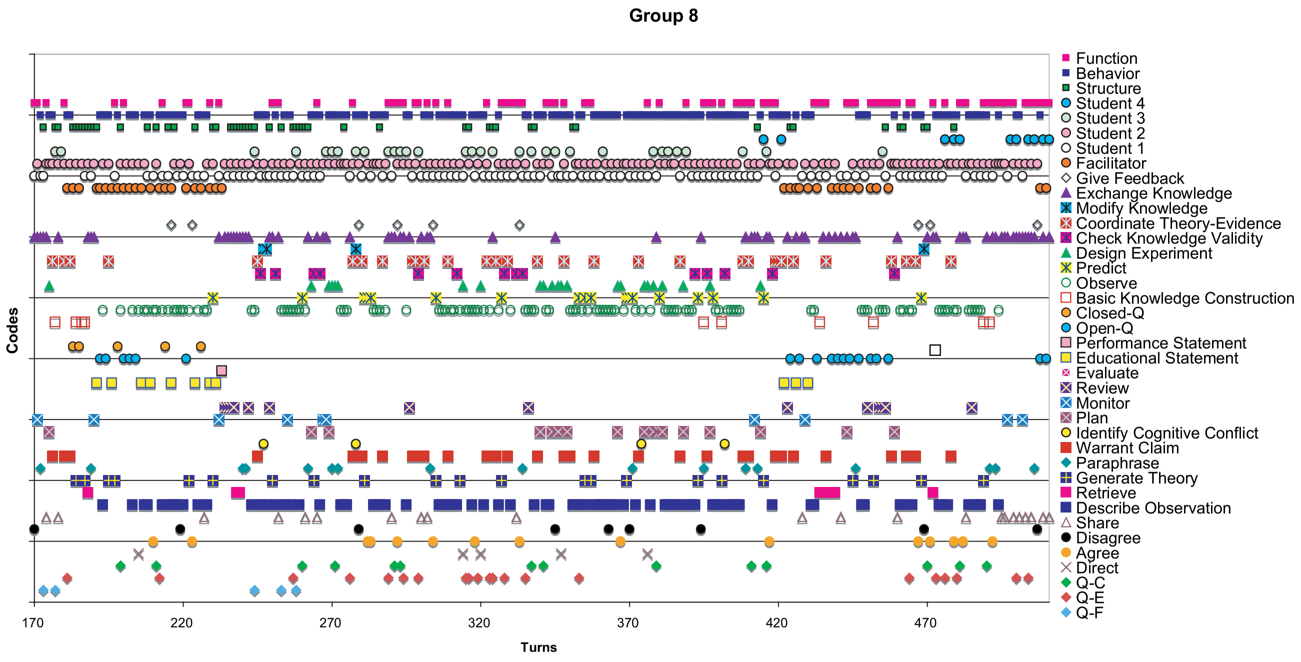


Figure 6. CORDTRA, high achieving group.

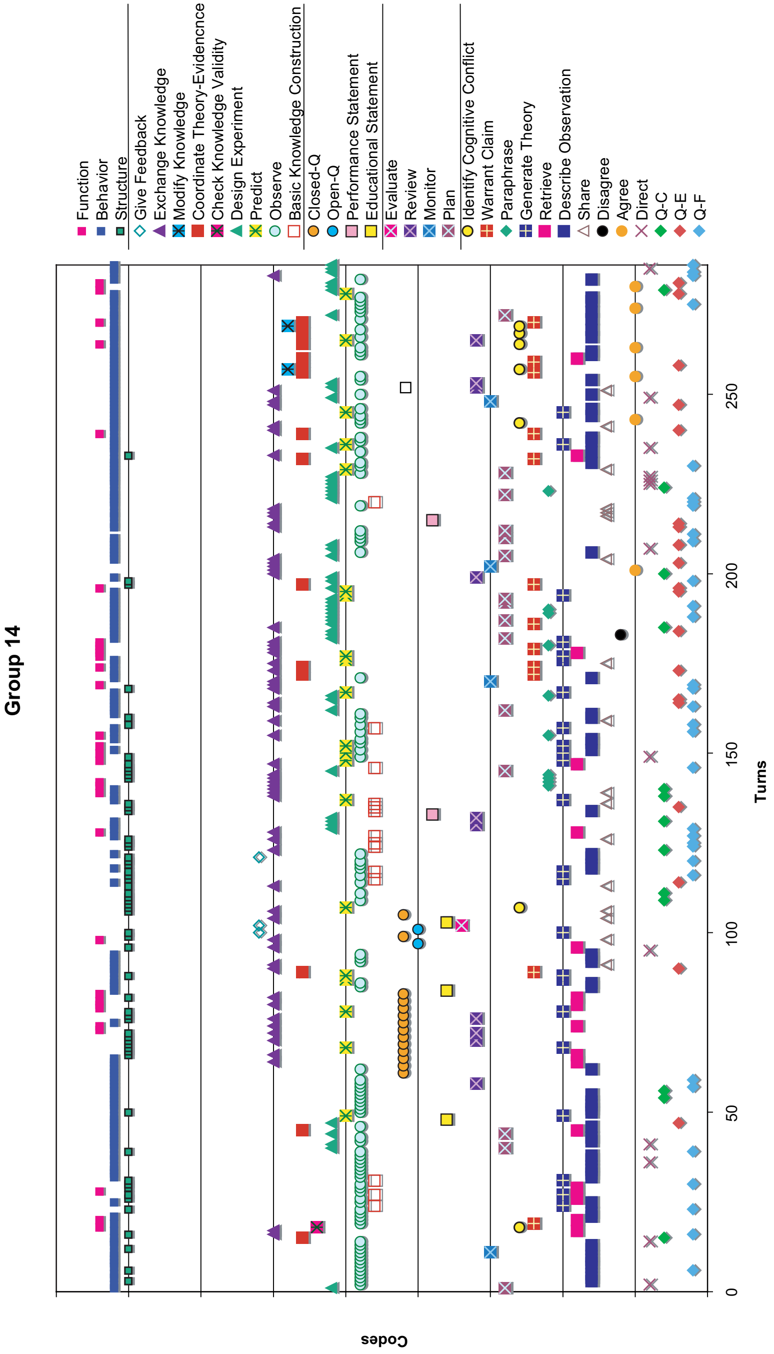


Figure 7. CORDTRA, low achieving group.

Our initial inspection suggested some places to go back to the transcript for analysis. In addition, this big picture made clear how some codes from the collaboration and epistemic practices categories were overlapping. It is not surprising that the "observe" and "describe observations" categories are almost completely overlapping. There was also some overlap between "warranting claims" and "coordinating theory and evidence", though this was more apparent in the high achieving group.

The process that we described here shows how CORDTRA diagrams provide information at a glance that is helpful at guiding further analysis. In the next sections, we will describe how further analysis was conducted and how we drew conclusions based on these diagrams and will compare with the results shown on the histograms.

5.2.2. *High achieving group*

Inspection of the CORDTRA diagram for group 8 (the high achieving group shown in Figure 6) showed that there was both an ongoing discussion of structures, behaviors, and functions and "describing observations." At about turn 270, there was increased engagement in epistemic practices of "designing experiments", "coordinating theory and evidence", and "checking knowledge validity". This change in the coded discourse suggested that we needed to go back to the transcript.

We did not expect the students to move between SBF levels so early in the discussion. In the early part of the discussion, the students talked in terms of observations about colored dots (which represent different chemicals: ammonia, nitrite, and nitrate in the simulation) and patches (which represent two types of bacteria) during the first half of the discussion; in the second half, the students began to talk more about what those patches represent. Further, Figure 6 demonstrates that the group conversation shifted across SBF levels and initially shifting largely between structures and behaviors, as they were trying to understand what was happening in the simulation. Inspection of Figure 6 also shows that associated with this shifting, the students often engaged in "exchanging knowledge," "warranting claims," and in the middle part of the discourse, with "designing experiments." This observation suggested the need to zoom into that initial part of the discourse both by looking at a section of the CORDTRA diagram, shown in Figure 8 and the actual transcript. The following example shows the group trying to figure out the interactive relations between the movement of the dots and the patches based on observations of the simulation:

203	Ada	So the white goes to the blue, but it doesn't matter. And the blue goes to the purple, and the red goes to anything...
	......	
207	Ada	The white one is going in the blue and nothing happens.
208	Siddarth	The red one...
209	Siddarth	So the white one goes into blue and nothing happens, right?
	......	
217	Ada	And then the yellow one, just...
219	Siddarth	The... red one goes into the purple and becomes white...
220	Siddarth	And then the white one goes into the blue one, and then becomes yellow.

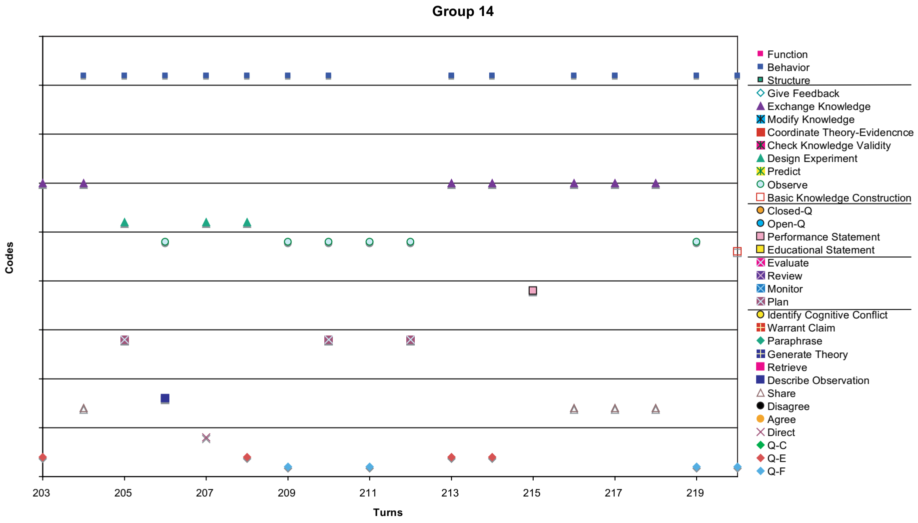


Figure 8. CORDTRA example excerpt 1.

In this segment, Ada and Siddarth were exchanging information about their observations as they discussed the structures and functions in the simulation. First Ada observed that red dots went into the blue patches and became white dots (turns 203 and 207, coded as behavior and observation). Then Siddarth noticed that white dots became yellow once they got into patches (turns 219 and 220). The discussion of the structures and behaviors of the dots and patches later became the supporting evidence for their meaning making of the representations of the bacteria in the model (i.e. the blue and the purple patches). The enlarged CORDTRA section in Figure 8 allowed the analyst to see what the major processes and content were in this early excerpt.

Inspection of the overall CORDTRA showed that there was a change in the pattern of the discussion late in the session that warranted further analysis. We zoom in on this part of the discussion in Figure 9. In this final section, the CORDTRA shows that the group discourse shifted between function and behavior as the students tried to construct explanations for their observations. Much of the shifting between levels occurred as students warranted claims and coordinated theory and evidence. In the example that follows, shown as the CORDTRA in Figure 9, the students were trying to make sense of the relation between fish, plants, and the nitrification process using the observations from the simulation as supporting evidence.

474 Siddarth No, look at the nitrate then look at the nitrite. The nitrate is increasing now. Wouldn't there be more nitrite when there is more ammonia? See if there is no plants it won't inflict the nitrite. Now if you add like... let's see if....
475 Ada still increasing...
476 Dhynani Why is ammonia decreasing? And now is increasing.
477 Siddarth Now let's see the bacteria... the bacteria is growing let's leave it a little bit.

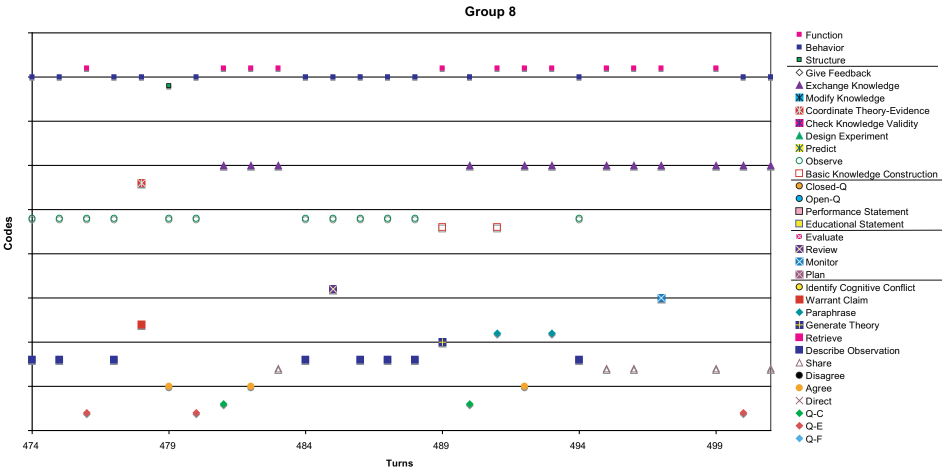


Figure 9. CORDTRA example excerpt 2.

478 Siddarth No, nitrite, stop because there is no purple.
479 Dhynani Yeah, there is no purple.
480 Siddarth There is no purple, so. . . what happened?
481 Dhynani So wait, so any thing. . . any of them is high then the fish die?
482 Siddarth Yeah, basically all of them hurt it.
483 Ada The only thing that helps the fish is the bacteria.
484 Siddarth I don't know if ours is right then. It looks like. . . what about if we change it to. . . when we change the water, change the water, change the water because there is no more ammonia. Oops, I just killed it now there is none.
485 Siddarth Ready? I'm going to click do. The purple pops out when exactly when the reds and the whites are there.
486 Ada So the high number of ammonia. . .
487 Siddarth Look, nitro is decreasing, decreasing. It stays on the same number nitrite stays around the same number, ammonia stays around the same number.
488 Ada Everything is around the same number, see. Because it goes up and down, and up and down. Ammonia is decreasing.
489 Siddarth So couldn't we theoretically say that. . . hum. . . if the environment remains the same when the plants and bacteria remaining stable, and fish remaining stable that the level will remain stable?
490 Ada Decreasing. If what?
491 Siddarth If bacteria, plants, and fish remain stable the aquatic ecosystem will remain stable, due to a a balance of functions, right?
492 Ada Yeah, a function created it. . .
493 Siddarth Due to a balance of functions, cause you are implying the functions.
494 Siddarth Look at the plant, is like been swamp with all these things going on.
495 Siddarth Fish, excrete ammonia to become nitrite.
496 Siddarth Nitrite helps the food when done the food.
497 Ada I know nitrite. . . plants need nitrite to. . .

. . . . . .

499 Siddarth They excrete ammonia and then the nitrite after they increase the nitrogen. Nitro becomes nitrite after. . . going through nitrofac. Nitrite is going to nitrofac, photosynthesis. Photosynthesis creates food and (inaudible) uses to create energy in cellular respiration. During. . . cellular respiration fish eat.
500 Dhynani How does it becomes nitrite?
501 Siddarth And then the nitrite goes to nitrobacteria and becomes nitrate.

In turn 478, Siddarth and Ada warranted a claim that nitrite would not occur because there were no purple patches in the model. This argument was based on previous discussion (turns 474–477) about the behaviors and functions of chemicals and the bacteria. In Line 474, Siddarth began by making a reference to the simulation and asked other group members to look at the nitrate. But by referring to the nitrate, he is actually referring to a simulation object (the yellow dot in the simulation) that she points to on the screen. At the same time, she is trying to describe her observations of the behavior. The next student, Ada asked about function in line 476 that led to Siddarth identifying a structure by using evidence from the simulation to warrant the claim (line 478). To further support their argument, they used the simulation to look for supporting observations (turns 479–488) and by discussing the behaviors and functions they generated a theory about why the system stays in a dynamic equilibrium (turn 489). After the theory was generated, the group started a cycle of sharing and confirming knowledge with each other about behaviors and functions (turns 490–501). Many questions posed in this example were explanation questions that asked about function.

For understanding the high-achieving group's collaborative activity, the CORDTRA diagram enabled us to determine that the students constructed an explanation in the end as they move towards explanations of function culminating in their attempt to integrate nitrification and photosynthesis. We speculate that the simulation was challenging what they knew, and that what they knew was not entirely accurate. They struggled between the notions that either their ideas or the simulation were wrong which suggests that they might have been using the simulation to wrestle with the difficult concepts involved to understand the aquarium system. We reached these conclusions through our interpretation of the CORDTRA diagrams and the pieces of transcript that the diagram suggested would be fruitful for further analysis.

5.2.3. *Low achieving group*

The CORDTRA diagram for the low achieving group is shown in Figure 7. In contrast to the high achieving group, we observed that this group began their discussion at the structural and behavioral level. They engaged in some discussion of function in the middle, but then ended with continued discussion of experimental designs, which were not driven by explicit goals and were not associated with shifting between SBF levels. This resulted in a discussion of behaviors that created a description rather than an explanation. Although there was an increase in explanation questions over time, these students were still asking many fact-oriented questions about what they directly observed. Again, we zoomed in to the CORDTRA enlarged in Figure 10. Similar to the high achieving group, the times when this group shifted between SBF levels was associated with knowledge exchange. Again, we include an excerpt from near the end of the group's work with the nitrification simulation.

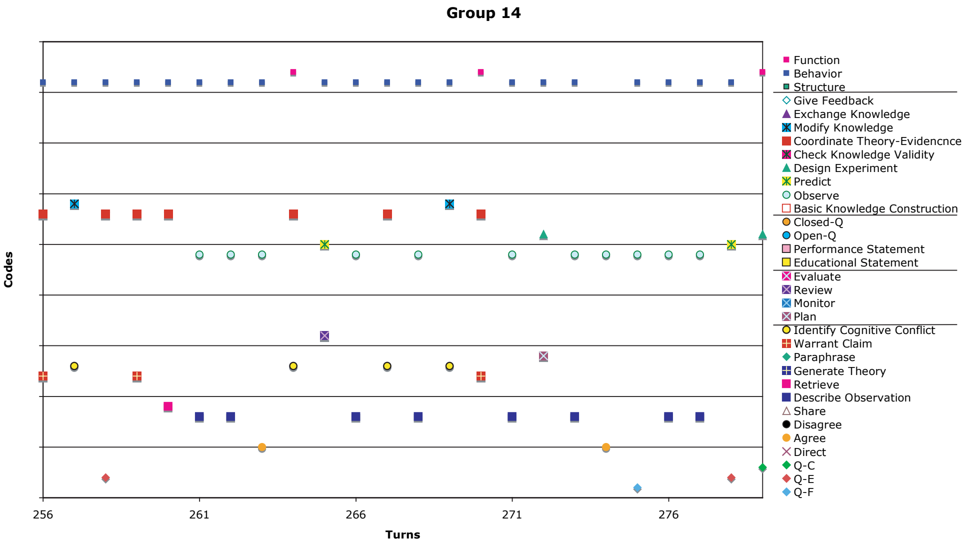


Figure 10. CORDTRA example excerpt 3.

256 Jean Look how high it is going because there is...
257 Judy But either way it went high
258 Jean Yea it speeds up even more with less amount of plants, but why? The whole cycle speeds up
259 Judy Because it didn't have anything to stop them...
260 Jean Yea you can have a group of plants it'd stop the fertilization, you'd like block them
261 Judy Exactly. Look the ammonia...
262 Judy Quicker
263 Robby Yea the ammonia went high really quick
264 Judy What wait look the plants eat... no the plants eat the nitrite but how come the nitrite isn't going up if the plants still eat it?
265 Jean Yea, I thought the nitrite would go up
266 Judy Nitrite is down... it hardy went down
267 Jean Yeah, it's the practically the same, which makes no sense
268 Robby All the acids are going up rapidly
269 Judy Our predictions were wrong for decrease.
270 Jean I put particularly because it's the cycle that is been affected
271 Judy Nitrite didn't go up at all, it is down
272 Let me see what happens if I change the water.
273 Judy Yea, all the ammonia and stuff goes down, and some of the nitrite and nitrate like basically everything goes down
274 Robby Okay
275 Judy wait does the bacteria change? What changes? Let me see
276 Jean The ammonia and the nitrite changes not the
277 Judy Are they kind of like wait... just give a lot and then...
278 Jean What would happen to the water...
279 Robby Why would I change it? What are we changing? Water?

In line 256, Jean began by describing the observed behavior in the simulation. They noticed associations between different behaviors of water quality indicators in the next several lines as they tried to coordinate theory and evidence and make predictions. The functional question asked in line 264 had the potential to lead to the construction of an explanation but the functional topic got lost in the group discussion as the groups went on to other predictions and describing behaviors through to the end of their discussion of this simulation. Although the discourse included many instances of warranting claims and identifying cognitive conflicts, a large portion of the discourse stayed at the behavioral level. The group was focusing on manipulating the simulations and observing relationships but not getting to the functional aspects that would let them construct an explanation. This CORDTRA analysis, as opposed to the inspection of the histograms, enabled us to generate an explanation why the low-achieving group had more discussion on behaviors but failed to reach a productive conversation.

Without comparing the different aspects of the discourse including the SBF content, the discourse and the epistemic practice features, it is unlikely that we would see the whole picture regarding the quality of the group collaboration. The CORDTRA diagram helped us to see the relations between SBF topics and the discourse and epistemic features, which leads to a thorough understanding of the collaborative process. This method affords a comprehensive understanding of students' discourse by looking into the interrelated aspects of students' engagement in collaboration, epistemic practices, and talking about different levels of science content (e.g. SBF).

6. Discussion

CORDTRA diagrams are a tool that can provide insight into the processes and activities in sociotechnical systems (Lemke, 2000). This representation helped point us to ways that we could thoughtfully combine different sources of data and analysis methods. Although the frequency counts show some ways in which the groups differ, the CORDTRA analysis is more informative in understanding how the collaborative activity unfolds, the role of content and its relationship to epistemic practices particularly by enabling us to compare multiple features of the data in a single view and across time. For example, a group could engage in discourse with a high frequency of warranting claims, often regarded as an indicator of a high quality discussion (Erduran, Simone, & Osborne, 2004), yet this might not be necessarily productive in developing explanations if the group did not discuss function (as shown in the low achieving group discourse example). Additionally, the CORDTRA diagram enables the researcher to focus on certain aspects of the conversation where students are engage in disagreement or cognitive conflict. Researchers can use the CORDTRA diagrams to isolate interesting points in the discussion for further analysis. As we saw in both groups, students came to the conversation with preexisting knowledge that conflicted with the simulations. These moments present an opportunity for instructor intervention.

The results from our contrasting case analysis enabled us to illuminate how different methodologies afford interpretation of differences between the high and low achieving groups as they worked with computer simulations. Characteristic of the high achieving group is that, when compared to a lower achieving group, they tended to recognize more of the structures, behaviors, and functions within the aquarium system. In addition, as shown through pre to posttest gains (Liu, 2008), they tended to provide more cohesive explanations for how system processes operate. This result is consistent with the results from multilevel data analysis indicating that warranting claims at the group level leads to improved individual learning outcomes (Liu, 2008). Although we cannot make any firm conclusions based on the analysis of two groups, we can generate hypotheses that would be interesting to follow up in the future. For example, explicitly guiding students through integrating structures and behaviors into functional processes enables deeper explanations. But as our CORDTRA analysis indicates, this instruction would likely be more productive after the process by which students share observations, exchange knowledge and check their own conceptual understanding (Schwartz & Bransford, 1998).

We have found CORDTRA diagrams to be a useful tool in studying how students negotiate meaning in collaborative groups and how this learning is mediated by technology (Suthers, 2006). Graphical representations can help researchers focus on interesting aspects of the discussion, as our examples showed (Dyke, Lund, & Girardot, 2009). CORDTRA was particularly helpful in understanding the importance of students' cycling between structure, behavior, and function levels as they construct descriptions and/or explanations. Explanations seem to occur as students both talk about function and coordinate theory-evidence, particularly late in the work with the simulation. This suggests that increased engagement in sophisticated epistemic practices, such as designing experiments, coordinating theory and evidence, and checking knowledge validity, may lead to productive collaborative discourse that generate warranted claims and explanations, which often involves talking about behavior and function in the simulation. These results lead us to generate hypotheses in need of further investigation, particularly given the limitation posed by the teacher differences between the two groups that we studied, and that we only studied two groups.

CORDTRA might also be used to inform our instructional designs. Because a goal in our research is to help students construct explanations, this analysis suggests that either our task design or facilitation needs to be modified to promote better coordination of theory and evidence as well as moving across SBF levels. For example, the results of our case studies show that discussion integrated between SBF levels leads to explanatory meaning making, which helps students understand the underlying science principles of the computer simulation. On the other hand, discussion that stays at the structural and behavioral level leads to superficial description of observations of the representations in the simulation. This suggests that to facilitate explanation, the teacher may need to ask questions to help students cycle between all three SBF levels.

Clearly, these results are tentative and require replication — but as part of our design work, these provide important information. Although we have discussed our findings from these case studies in great detail, we reiterate that this technique could be used with a wide range of coding schemes and log data that should be based on the researcher's goals. One limitation of these diagrams is that they are quite time consuming to construct and require discourse data. We suspect that they would be even more informative if we could include digital log data as well, as other studies have demonstrated (Hmelo-Silver *et al.*, 2008). These could also be valuable for formative assessment, particularly in online environments if creating these diagrams can be automated. Tools such as Tatiana offer great potential by helping researchers manage, synchronize, and analyze multiple forms of data as well as creating visualizations to assist in data interpretation (Dyke *et al.*, 2009). Such tools offer great advantages in terms of ease of use and filtering that do not exist in a commercial spreadsheet which is a more general-purpose tool. Nonetheless, our hope is that CORDTRA can be a useful tool to help researchers better understand how technology mediates collaborative learning as well as providing a representation that can be useful in identifying where the action is in group discourse and how utterances combine over time to create a learning conversation (Lemke, 2000; Stahl, 2006).

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