Effects of Alternate Representations of Evidential Relations on Collaborative Learning Discourse

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Abstract: Over the past decade or so, a number of software environments have been created to support students engaged in collaborative investigations in science (e.g., Belvedere, CoVis, CSILE, SenseMaker, and WebCamile). These environments have used a variety of representations for recording information such as alternate hypotheses, empirical observations, and evidential relations (e.g., node-link graphs, structured lists, and containers). There are both empirical and theoretical reasons to believe that the expressive constraints imposed by a representation and the information (or lack of information) that a representation makes salient may have important effects on students' discourse during collaborative learning. However, to date no systematic study has been undertaken to explore possible effects. This paper outlines a research agenda to address this need; provides theoretically motivated predictions; and reports initial results from a pilot study. Students worked together in groups of two on hypertext-based "science challenge" problems. Two groups used each of free text (MS Word), matrix (Excel) or graph (Belvedere) representations of evidence, for a total of six groups. Analysis of discourse transcripts suggests that these representations have quite different effects on the extent to which students discuss evidential relations.

Keywords: HCI, discourse analysis, representational tools

Introduction

For a number of years, the author and his colleagues (see acknowledgments) have been building, testing, and refining a diagrammatic environment ("Belvedere") intended to support secondary school children's learning of critical inquiry skills in the context of science. The diagrams were first designed to capture scientific argumentation, and later simplified to focus on evidential relations between data and hypotheses. This change was driven in part by a refocus on *collaborative* learning, which led to a major change in how we viewed the role of the interface representations. Rather than being a medium of communication or a formal record of the argumentation process, we came to view the representations as resources (stimuli and guides) for conversation (Roschelle, 1994; Suthers, 1995).

Meanwhile, various projects with similar goals (i.e., critical inquiry in a collaborative learning context) were using radically different representational systems (Bell, 1997;

Guzdial *et al.,* 1997; O'Neill & Gomez, 1994; Scardamalia *et al.,* 1992; Suthers *et al.,* 1997). There are both empirical and theoretical reasons, some of which are summarized in this paper, to believe that the expressive constraints imposed by a representation and the information (or lack of information) that a representation makes salient may have important effects on students' discourse during collaborative learning. However, to date no systematic study has been undertaken to explore possible effects of this variable on collaborative learning. This paper motivates and describes such a study being undertaken by the author and reports initial results from a pilot study.

Representations in critical inquiry software

To provide examples and motivation for discussion, several alternate representational approaches taken in computer supported collaborative learning (CSCL) systems for critical inquiry are characterized below.

Hypertext/hypermedia systems include CLARE (Wan & Johnson, 1994), CSILE (Scardamalia *et al.,* 1992), the Collaboratory Notebook (O'Neill & Gomez, 1994), and Web-Camile and Web-SMILE (Guzdial *et al.,* 1997). (Seminal systems include gIBIS (Conklin & Begeman, 1987) and NoteCards (Harp & Neches, 1988), which were not developed for educational applications.) These systems all have in common a linking of different comments relevant to an issue, usually with categorization of the hyperlinks or their targets with labels. There is wide variation in this category: some take the form of a threaded discussion or other tree structure that may be viewed in summary form (see Figure 1a for a characterization), while others support construction of graphs of "nodes" or "cards" through which one navigates, viewing one card at a time. Mature systems such as CSILE or its successor, Knowledge Forum, use several of the representational approaches discussed herein.

Several argument mapping environments, including Belvedere (Suthers *et al.,* 1997; Suthers & Weiner, 1995), ConvinceMe (Ranney *et al.,* 1995), and Euclid (Smolensky *et al.,* 1987), utilize node-link graphs representing rhetorical, logical, or evidential relationships between assertions (usually categorized as "hypothesis" versus "data" or "evidence"). Belvedere is characterized in Figure 1c: rounded shapes represent hypotheses and rectangles represent empirical observations. The entire graph is viewed and manipulated at once, distinguishing these systems from hypermedia environments in which one normally works with one node of the graph at a time.

SenseMaker (Bell, 1997) exemplifies an intermediate approach between graphs and hierarchies. Statements are organized in a 2-dimensional space and viewed all at once, as in argument graphs (see Figure 1b). However, SenseMaker uses containment rather than links to represent the relationship of evidential support: an empirical statement is placed inside the box of the theory it supports. SenseMaker also uses containment to represent decomposition of a theory into hypotheses, a feature that was tried in early versions of Belvedere.

Finally, another representation is an evidence or criteria matrix. Several forms are possible. One organizes hypotheses along one axis, and empirical evidence along another, with matches between the two being expressed symbolically in the cells of the matrix (e.g., Figure 2c). Puntambekar *et al.* (1997) experimented with a matrix representation in a paper-based collaboration tool.

The differences in representational notations provided by existing software for critical inquiry is striking. Yet more striking is the fact that there appear to be no systematic studies *comparing* the effects of external representations on collaborative learning discourse. Exceptions include (Guzdial, 1997; Wojahn *et al.,* 1998). Given that these representations define the fundamental character of software intended to guide learning, a systematic comparison is overdue.

Substantial research has been conducted concerning the role of external representations in individual problem solving, generally showing that the kind of external representation used to depict a problem may determine the ease with which the problem is solved (Koedinger, 1991; Kotovsky & Simon, 1990; Larkin & Simon, 1987; McGuiness, 1986; Zhang, 1997). One might ask whether this research is sufficient to predict the effects of representations in collaborative learning. A related but distinct line of work undertaken in collaborative learning contexts is needed for several reasons. The interaction of the cognitive processes of several agents is different than the reasoning of a single agent (Okada & Simon, 1997; Perkins, 1993), so may be affected by external representations in different ways. In particular, shared external representations can be used to coordinate distributed work, and will serve this function different ways according to their representational biases. Also, the mere presence of representations in a shared context with collaborating agents may change each individual's cognitive processes. One person can ignore discrepancies between thought and external representations, but an individual working in a group must constantly refer back to the shared external representation while coordinating activities with others. Thus it is conceivable that external representations have a greater effect on individual cognition in a social context than they do when working alone (Micki Chi, personal communication). Finally, much prior work on the role of external representations in individual problem solving has used well-defined problems. Further study is needed on ill structured, open-ended problems such as those typical of scientific inquiry.

Representational bias

This section sketches a theoretical perspective to guide the research agenda, beginning with definitions. *Representational tools* are artifacts (such as software) with which users construct, examine, and manipulate external representations of their knowledge. The present work is concerned with symbolic as opposed to analogical representations. A representational tool is an implementation of a *representational notation* that provides a set of primitive elements out of which representations can be constructed. Developers choose a representational notation and instantiate it as a representational tool, while the user of the tool constructs particular *representational artifacts* in the tool. The present

work focuses on interactions between learners and other learners, specifically verbal and gestural interactions termed *collaborative learning discourse.*

Each given representational notation manifests a particular *representational bias,* expressing certain aspects of one's knowledge better than others (Utgoff, 1986). The phrase *knowledge unit* is used to refer generically to components of knowledge one might wish to represent, such as hypotheses, statements of fact, concepts, relationships, rules, etc. Representational bias manifests in two major ways: *Constraints:* limits on logical expressiveness, and in the sequence in which knowledge units can be expressed (Reader, unpublished, Stenning & Oberlander, 1995); and *Salience:* how the representation facilitates processing of certain knowledge units, possibly at the expense of others (Larkin & Simon, 1987). Representational tools mediate collaborative learning discourse by providing learners with the means to articulate emerging knowledge in a persistent medium, inspectable by all participants, where the knowledge then becomes part of the shared context. Representational bias constrains the knowledge that can be expressed in the shared context, and makes some of that knowledge more salient and hence a likely topic of discussion. Sources of constraint and salience are discussed below.

Zhang (1997) distinguishes *cognitive* and *perceptual* operators in reasoning with representations. Cognitive operations operate on internal representations; while perceptual operations operate on external representations. Perceptual operations take place without making an internal copy of the representation, although internal representations may change as a result of these operations. Expressed in terms of Zhang's framework, the present work is concerned primarily with perceptual operations on external representations: the question is how representations that reside in learners' perceptually shared context mediate collaborative learning discourse. While it is the case that cognitive operations on internal representations will influence interactions in the social realm, CSCL system builders do not design internal representations ñ they design tools for constructing external representations.

Stenning and Oberlander (1995) distinguish constraints inherent in the logical properties of a representational notation from constraints arising from the architecture of the agent using the representational notation. This corresponds roughly to the present author's distinction between "constraints" and "salience." Constraints arise from logical limits on the information that can be expressed in the representational notation, while salience arises from how easily the agent recovers the information (via perception) from the representational artifacts. Information that is recoverable from a representation is salient to the extent to which it is recoverable by automatic perceptual processing rather than through a controlled sequence of perceptual operators (Lohse, 1997, Zhang, 1997).

The discussion now turns to predictions based on differences between representational notations.

Notations have ontological bias

The first hypothesis claims that important guidance for collaborative learning discourse comes from ways in which a representational notation *limits* what can be represented

(Reader, unpublished; Stenning & Oberlander, 1995). A representational notation provides a set of primitive elements out of which representational artifacts are constructed. These primitive elements constitute an "ontology" of categories and structures for organizing the task domain. Learners will see their task in part as one of making acceptable representational artifacts out of these primitives. Thus, they will search for possible new instances of the primitive elements, and hence (according to this hypothesis) will be biased to think about the task domain in terms of the underlying ontology. Ontological bias will not be addressed further in this paper.

Salient knowledge units are elaborated

This hypothesis states that learners will be more likely to attend to, and hence elaborate on, the knowledge units that are perceptually salient in their shared representational workspace than those that are either not salient or for which a representational proxy has not been created. The visual presence of the knowledge unit in the shared representational context serves as a reminder of its existence and any work that may need to be done with it. Also, it is easier to refer to a knowledge unit that has a visual manifestation, so learners will find it easier to express their subsequent thoughts about this unit than about those that require complex verbal descriptions (Clark & Brennan, 1991). These claims apply to any visually shared representations. However, to the extent that two representational notations differ in kinds of knowledge units they make salient, these functions of *reminding* and *ease of reference* will encourage elaboration on different kinds of knowledge units.
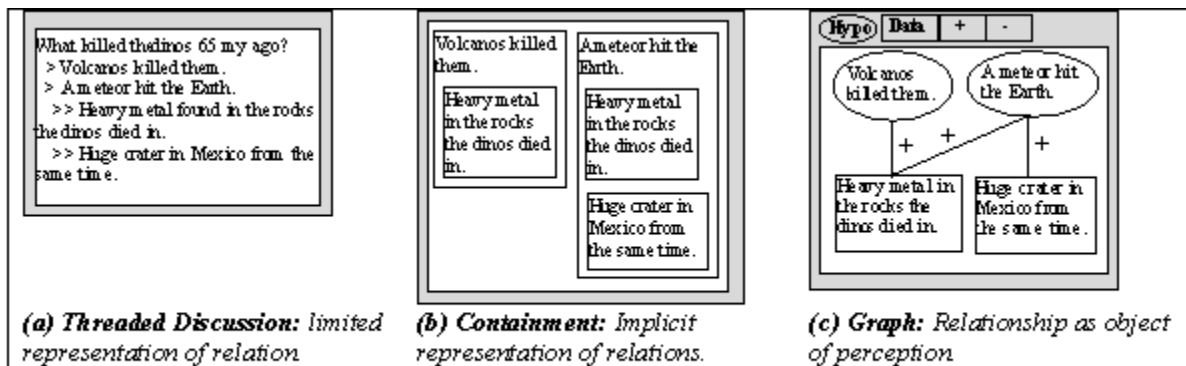

Figure 1. Example of Elaboration Hypothesis

For example, consider the three representations of a relationship between four statements shown in Figure 1. The relationship is one of evidential support. The middle notation uses an implicit device, containment, to represent evidential support, while the right-hand notation uses an explicit device, an arc. It becomes easier to perceive and refer to the *relationship* as an object in its own right as one moves from left to right in the figure. Hence the present hypothesis claims that relationships will receive more elaboration in the rightmost representational notation.

The opposite prediction is also plausible. Learners may see their task as one of putting knowledge units "in their place" in the representational environment. For example (according to this competing hypothesis), once a datum is placed in the appropriate hypothesis container (Figure 1b) or connected to a hypothesis (Figure1c), learners may feel it can be safely ignored as they move on to other units not yet placed or connected. Hence they will not elaborate on represented units. This suggests the importance of making missing information salient.

Salience of missing units guides search

Some representational notations provide structures for organizing knowledge units, in addition to primitives for construction of individual knowledge units. Unfilled "fields" in these organizing structures, if perceptually salient, can make missing knowledge units as salient as those that are present. If the representational notation provides structures with predetermined fields that need to be filled with knowledge units, the present hypothesis predicts that learners will try to fill these fields.

For example, Figure 2 shows artifacts from three notations that differ in salience of missing evidential relationships. In the textual representation, no particular relationships are salient as missing: no particular prediction about search for new knowledge units can be made. In the graph representation, the lack of connectivity of the volcanic hypothesis to the rest of the graph is salient. Hence this hypothesis predicts that learners will discuss its possible relationships to other statements. However, once some connection is made to the hypothesis, it will appear connected, so no further relationships will be sought. In the matrix representation, all undetermined relationships are salient as empty cells. The present hypothesis predicts that learners will be more likely to discuss many relationships between statements when using matrices.
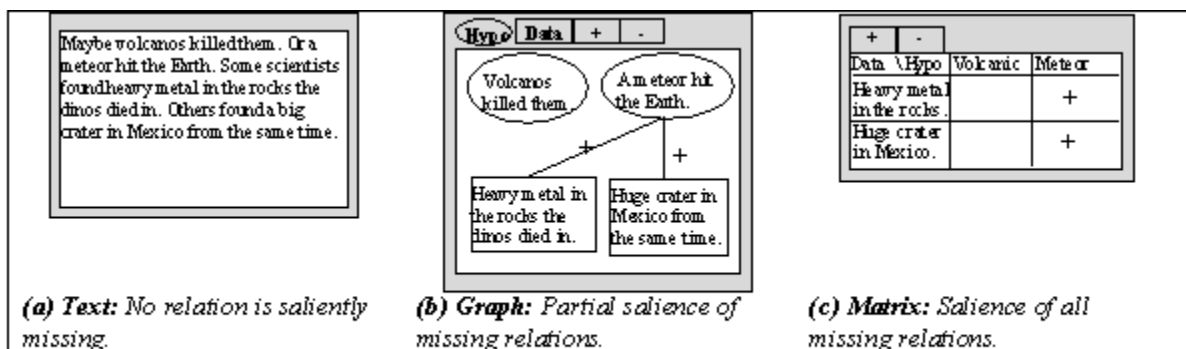

(a) Text: *No relation is saliently missing.*

(b) Graph: *Partial salience of missing relations.*

(c) Matrix: *Salience of all missing relations.*

Figure 2. Example of Salient Absence Hypothesis

Empirical studies

The author has begun studies that test the effects of representational notations on collaborative discourse and learning. The question is not "what system is better?" but

rather "what kinds of interactions, and therefore learning, does each representational notation encourage?" It may well be the case that all of the above representations are useful, albeit for different learning and problem solving phases or task domains.

The studies intentionally use representations that differ on more than one feature, as summarized in Table 1. The research strategy is to maximize the opportunity to observe predicted effects on learners' discourse, in order to explore the large space of experimental comparisons within the time scale on which collaborative technology is being adapted. These results will then inform well-motivated selection of studies that vary one feature at a time as needed to disambiguate alternate representational explanations for the results.

Table 1. Features of Selected Representational Formalisms

	Threaded	Containers	Graphs	Matrices
Organization of Inquiry Activity	Discussion topics are posted, followed by chronologically organized replies.	Hypotheses are first recorded as boxes in the workspace. Empirical observations are sorted by placing them in boxes.	Hypotheses and empirical observations are recorded at any time as shapes placed in the workspace. Evidential relations are recorded by linking shapes together.	Hypotheses and empirical observations are recorded at any time by creating new columns & rows (respectively). Evidential relations are recorded by placing symbols in empty cells.
Ontology	Implicit: ♦ statements ♦ reply chronology	Implicit: ♦ hypothesis ♦ empirical observation ♦ consistency	Explicit: ♦ hypothesis ♦ empirical observation ♦ consistency ♦ inconsistency	Explicit: ♦ hypothesis ♦ empirical observation ♦ consistency ♦ inconsistency
Salience of Known Relations	Implicit in Context: ♦ reply chronology	Implicit in Context: ♦ consistency	Explicit Object: ♦ consistency ♦ inconsistency	Explicit Object: ♦ consistency ♦ inconsistency
Salience of Missing Relations	No salience.	Lack of *some* consistency relation for a hypothesis.	Lack of *some* consistency or inconsistency relation for a statement.	Relations for *all combinations* of hypothesis and empirical observation.

Experimental materials and procedure

A pilot study was conducted comparing MS Word (unstructured text), MS Excel (tables), and Belvedere (graphs), with two pairs of subjects run in each condition. (Early results of the pilot are reported below.) Future experiments will use versions of Belvedere that have been modified to provide the alternative representations in Table 1. This approach will reduce nonessential differences between the representational tools, and enable uniform recording of all manipulations of the representations in the Belvedere server database.

Subjects are presented with a "science challenge problem" in a web-browser. A science challenge problem presents a phenomenon to be explained (e.g., determining the cause of a mysterious disease), along with indices to relevant resources. It is important that these are relatively ill-structured problems: at any given point many possible knowledge units

may reasonably be considered. This provides the necessary degrees of freedom within which representational bias can work.

One side of the computer screen contains the representational tool, such as Text, Containment, Graph, or Matrix. The other side contains a web browser open to the entry page for the science challenge materials. Students seated in front of the monitor are asked to read the problem statement in the web browser. They are then asked to identify hypotheses that provide candidate explanations of the phenomenon posed, and evaluate these hypotheses on the basis of laboratory studies and field reports obtained through the hypertext interface. They are asked to use the representational tool to record the information they find and how it bears on the problem. The session is videotaped with the camera pointed at the screen over the shoulder of one of the participants. The camera is adjusted to show the screen in sufficient detail to see its contents, yet also show the immediate space around the screen to capture gestures in the vicinity of the screen. At the conclusion of the problem solving session, subjects are asked to write a brief essay and take a content knowledge test. Analysis is based on transcripts of subjects' spoken discourse, gestures, and modifications to the interface; as well as measures of learning outcomes (not discussed in this paper).

Pilot study results

The pilot data is currently under analysis. The purpose of this analysis is twofold: to identify trends suggesting that there is a phenomenon worthy of further study; and to refine analytic techniques. At this writing, pilot study videotapes from the six one-hour problem solving sessions have been transcribed and segmented, and limited coding has been completed. A segment was defined to be a gesture, a modification to the external representation, or a single speaker's turn in the dialogue, except that turns that expressed multiple propositions were broken into multiple segments. Segments were coded on the following dimensions (among others), using the QSR Nud*ist software package.

> **Representation:** *Values include Graph, Matrix, Text. This coding applies to an entire transcript, and indicates the independent variable for the session.*

> **Mode:** *This dimension is used to filter and select segments for particular hypothesis tests. Values include Verbal, Gestural, and Representational (modifications to the software representations).*

> **Evidential Content:** *Values include Consistent, Inconsistent, Choice. Identification of segments where subjects discuss or identify the nature of the evidential relationship between two statements as being one of consistency or inconsistency; or raise the question of which relationship holds.*

A coarse-grained test of the Search hypothesis was conducted as follows. Recall that Search predicts that subjects will be more likely to seek evidential relations when using representations that prompt for these relations with empty structure (Text < Graph <

Matrix). This analysis simply counted, for each treatment group, the percentage of verbal segments that were coded with any one of the three Evidential values (Consistent, Inconsistent, Choice). The results are shown in Table 2.

Table 2: Frequency Data for Evidential Statements

Tool	Group	Verbal Segments	Duration (Sec)	Evidence Segments	
Text	5	200	2668	0	0%
	6	617	3706	13	2%
		817	6374	13	2%
Graph	1	396	2801	18	5%
	2	227	1940	12	5%
		623	4741	30	5%
Matrix	3	76	2526	1	1%
	4	550	2671	52	9%
		626	5197	53	8%

Examining the percentage of verbal segments that are concerned with evidence (rightmost column), the results appear to be consistent with the Search hypothesis (Text < Graph < Matrix). Although this trend is encouraging with respect to the question of whether there is a phenomenon worth investigating, this sample data cannot be taken as conclusive. Caveats (all of which are being addressed by ongoing work) include the small sample size (hence no test of significance), the lack of multiple coders (hence no test of inter-rater reliability), the need to test learning outcomes, and the need for a more direct test of the claim that representational state affects subsequent discourse processes. Analyses that are based on frequencies of utterances across the session as a whole fail to distinguish utterances seeking evidential relations from those elaborating on previous ones (i.e., between the Search and Elaborate hypotheses), or to show a causal relationship between the state of the representation and the subsequent discourse. A more sophisticated coding is required to test whether the representation or salient absence of a particular (kind of) knowledge unit influences search for or elaboration on that unit. This problem will be addressed as follows. Every change to the representations will be coded with the set of knowledge units that are (a) expressed or (b) saliently missing from that point onwards to the next change. Then, subsequent utterances within a time-window defined by a decay function will be tested for either (a) elaboration on those knowledge units or (b) search for other knowledge units related by evidential relations. This provides a more stringent test of the causal relationship between salience and discourse claimed by the research hypotheses.

Qualitative observations

Examples and discussion of the artifacts created and of transcripts are provided here to help illustrate the predicted effects and related issues.

The document created by group 5 (text) had no expression of evidential relations between the hypotheses and data, and there was no overt discussion of evidential relations in the transcript of verbal discourse. All of the discussion of evidence in the text condition occurred in group 6 at the end of their session (the longest session in the pilot study), when the subjects spontaneously identified a hypothesis impacted by each datum gathered.

A document produced by group 1 (graph) is reproduced in Figure 3, followed by a portion of the corresponding transcript in Table 3. Note the linearity of the graph (normally considered a nonlinear medium). The pattern of *{identify, categorize, add, link}* seen in the transcript (underlined) is typical of interactions in this transcript. This pattern of activity, which leads to the linearity of the graph, is consistent with the competitor to the Elaboration hypothesis: subjects may feel that the primary task is to connect each new statement to something else, after which it can be ignored.
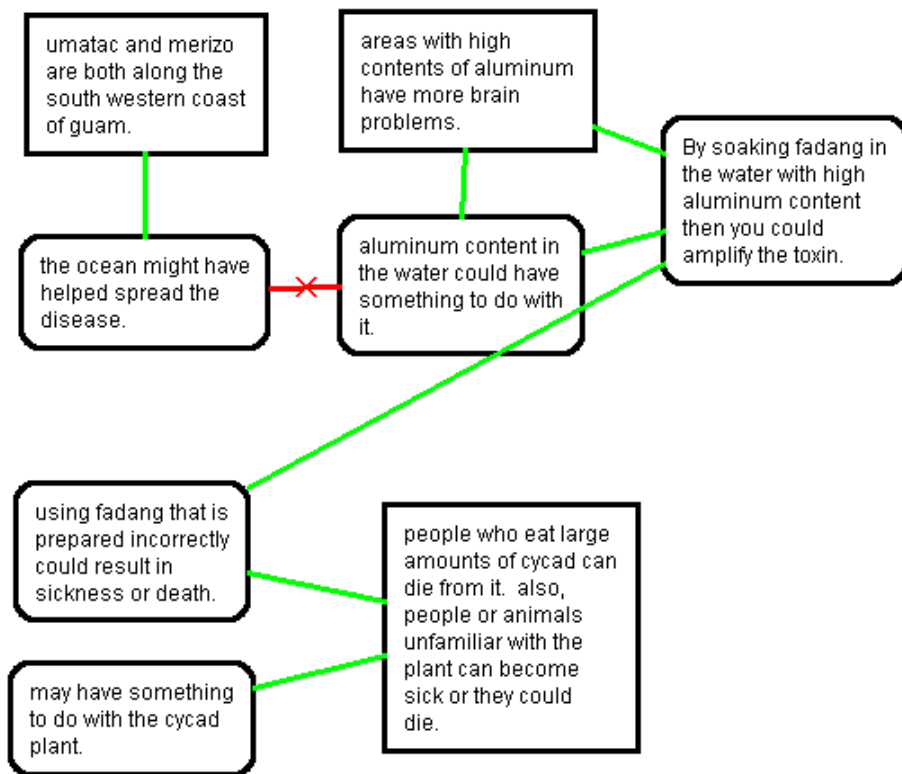

Figure 4. Group 1's Graph

Table 3. Group 1's Transcript Sample

```
L  look, everybody knows that fadang is a toxic; people who go to
   a lot of trouble to for…
R  Yeah, that means that, uh, if they don't do it right, they..
L  they could die; that might not cause the disease, though
R  it's a hypothesis <typing hypothesis in text box>
L  what if they don't prepare it right?
R  right
L  oops
R  okay, hunh?
L  <m>
R  <m>, this?  add  to our investigation?
L  yeah, add to investigation <adding for link>; and that also
   goes to cyad, too
R  well, wait, uh
L  hold over <placing for link between D and H>
R  and this stuff is the same thing as fadang, right?
L  yeah
```

Finally, a matrix produced by group 4 (Excel) is reproduced in Table 4, followed by a portion of the group's transcript in Table 5. Table 4 is especially striking because students were not specifically instructed to fill in all the cells. In the transcript, note the systematic identification of evidential relations as students work down the column, and the appropriate use of the column to rule out a hypothesis that the students proposed (radiation from atomic bombs caused disease, second column).

Table 4. Group 4's Matrix

Research Question:	What causes neurulogical diseases?			
Hypotheses / Data	food poisoning found in Central America- FADANG	radiation from Hiroshima/Nagasoki in the Pacific	diet in The south Pacific	nerve tangles found in spinal cords causing desease, similar to Alziemer's
nutritionist claims that chamorros, found in FADANG, killed several people	confirm	conflict	confirm	conflict
Nutritionist claims that lack of Calcium in Pacific region causes brain desease	conflict	conflict	confirm	conflict
spinal/brain disfunctions causing desease	conflict	conflict	conflict	confirm
Certain Amino Acids found in food (peas) cause disfunction in the brain	confirms	conflicts	confirms	confirms
Test between 1941-1945 proved that all patients in the hospital were Chamorro and had ALS	confirms	conflicts	confirms	confirms

Table 5. Group 4's Transcript Sample

```
R Found in chickling peas.  Chickling peas...
L Peas.  All right. <points to screen> Now.  What hypothesis is
  this?  Food poisoning.  Yeah.  Okay. Go down. Let's see.
  Supports.
R Confirms.  Confirm.  You might want to use the same word
  you're using the whole time.
L Is there any chance we could use this for the science fair?  No.
  It conflicts.
R Diet in South Pacific, yes?
L No, no, no, no, no. <points to screen>
R Conflicts and then confirms.
L Conflicts.  Is it.  Confirms.  What is this one?  Oh, the brain.
R Well, yeah.
L Yeah, yeah.  Okay.  Confirms.  Well, I think now we should,
  like, rule out this <points to hypothesis in table> one because it
  has had nothing but conflicts.  The Hiroshima ...that we thought
  of ourself.
R It conflicts, conflicts, conflicts.  It hasn't had one, uh...
```

Summary

Prior experience with Belvedere suggested that variation in features of the representational tools can have a significant effect on the learners' knowledge-building discourse and on learning outcomes. The paper sketched a theoretical analysis of the role of constraints and salience in representational bias, outlined an investigation being undertaken by the author, and reported promising but preliminary results of a pilot study. Continued work in this area will inform the design of future software learning environments and provide a better theoretical understanding of the role of representational bias in guiding learning processes.

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