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Towards a Systematic Study of Representational Guidance for Collaborative Learning Discourse[1]

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Abstract: The importance of collaborative and social learning processes is well established, as is the utility of external representations in supporting learners' active expression, examination and manipulation of their own emerging knowledge. However, research on how computer-based representational tools may support collaborative learning is in its infancy. This paper motivates such a line of research, sketches a theoretical analysis of the roles of constraint and salience in the representational guidance of collaborative learning discourse, and reports on an initial study that compared textual, graphical, and matrix representations. Differences in the predicted direction were observed in the amount of talk about evidential relations and the use of epistemological categories.

Keywords: collaborative learning, representational bias, visual languages
Category: K.3.1

1 Introduction

Research into the cognitive and social aspects of learning has developed a clear picture of the utility of external representations in supporting learners' active expression, examination, and manipulation of their own knowledge (e.g., [Koedinger 1991], [Novak 1990], [Reusser 1993], [Scardamalia et al. 1992], [Snir et al. 1995]), as well as the equal importance of collaborative and social learning processes (e.g., [Brown and Campione 1994], [Lave and Wenger 1991], [Slavin 1980], [Webb and Palincsar 1996]). Yet, there is insufficient research on how these two techniques may be constructively combined. In this paper I motivate and introduce a line of research on *representational tools in support of collaborative learning*.

Representational tools range from basic data manipulation and office tools such as spreadsheets and outliners to knowledge mapping software and enhanced modeling and simulation tools. Such tools can help learners see patterns, express abstractions in concrete form, and discover new relationships. Ideally, they function as *cognitive* tools that lead learners into knowledge-building interactions [Collins and Ferguson 1993], [Lajoie and Derry 1993]. My research is based on the hypothesis that properly designed representational tools can guide collaborative as well as individual learning interactions. Specifically, when learner-constructed external representations become part of the collaborators' shared context, the distinctions and relationships made

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salient by these representations may guide their interactions in ways that influence learning outcomes.

Collaborative learning has been shown to correlate with greater learning, increased productivity, more time on task, transfer of knowledge to related tasks, and higher motivation [Johnson and Johnson 1989], [Rysavy and Sales 1991], [Sharan 1980], [Slavin 1980], provided that the learning groups and tasks are well chosen [see Webb and Palincsar 1996]. Similarly, collaborative use of instructional software (often necessary in primary and secondary education due to limited availability of equipment) can be at least as effective as individual use [Johnson et al. 1985], [Justen et al. 1990], [Webb 1989]. In postsecondary distance education, electronic forms of collaborative learning can help reduce the isolation of telecommuting learners and increase the interactivity of the distance learning experience [Abrami and Bures 1996], [Jonassen et al. 1995]. Nevertheless, we cannot expect learning gains just because learners are sitting together or connected by a wire. A goal of computer supported collaborative learning (CSCL) systems [Koschmann 1994], [Pea 1994] and of my work is to improve the effectiveness of collaborative learning as an instructional format: i.e., to support peer interactions in a manner that increases learning gains.

For a number of years, my colleagues and I have been building, testing, and refining a diagrammatic environment ("Belvédère") intended to support secondary school children's learning of critical inquiry skills in the context of science [Suthers and Weiner 1995], [Suthers et al. 1997], [Toth et al. 2001]. The diagrams were first designed to capture scientific argumentation during interaction with an intelligent tutoring system, 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 diagrammatic representations. Rather than viewing the representations as medium of communication or a formal record of the argumentation process, we came to view them 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, such as various forms of hypertext/hypermedia [Guzdial et al. 1997], [O'Neill and Gomez 1994], [Scardamalia et al. 1992], [Wan and Johnson 1994], node-link graphs representing rhetorical, logical, or evidential relationships between assertions [Ranney et al. 1995], [Smolensky et al. 1987], [Suthers and Weiner 1995], containment of evidence within theory boxes [Bell 1997], and evidence or criteria matrices [Puntambekar et al. 1997].

Both empirical and theoretical inquiry suggest that the expressive constraints imposed by a representation and the information (or lack thereof) that it makes salient may have important effects on students' discourse during collaborative learning. Specifically, as learner-constructed external representations become part of the collaborators' shared context, the distinctions and relationships made salient by these representations may influence their interactions in ways that influence learning outcomes. However, to date little systematic research has undertaken to explore possible effects of this variable on collaborative learning. One exception is [Guzdial 1997], who undertook a comparison of two forms of threaded discussion. Given that external representations define the fundamental character of software intended to

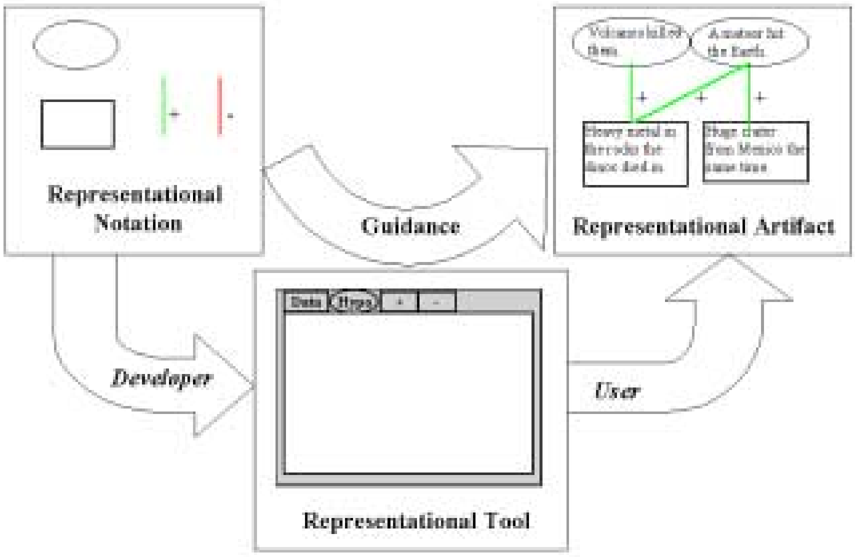


Figure 1: Representational Guidance

guide collaborative learning, a systematic comparison is overdue. The question is *not* "which representation is better?" but rather "what kinds of interactions, and therefore learning, does each representational notation encourage?" This paper motivates a research program and reports initial results from our laboratory.

2 Representational Guidance

The major hypothesis of this work is that variation in features of representational tools used by learners working in small groups can have a significant effect on the learners' knowledge-building discourse and on learning outcomes. The claim is not merely that learners will talk about features of the software tool being used. Rather, with proper design of representational tools, this effect will be observable in terms of learners' talk about and use of subject matter concepts and skills. I have begun investigations to determine what features have what kind of effect. This section develops an initial theory of how representations guide learning interactions, and applies this analysis to make specific predictions concerning the effects of selected features of representational tools. The discussion begins with some definitions.

2.1 Definitions

Representational *tools* are software interfaces in which users construct, examine, and manipulate external representations of their knowledge. My work is concerned with symbolic as opposed to analogical representations. A notation/artifact distinction [Stenning and Yule 1997] is critical, as depicted in [Fig. 1]. A representational tool is a software implementation of a representational *notation* that provides a set of primitive elements out of which representations can be constructed. (For example, in [Fig. 1], the representational notation is the collection of primitives for making hypothesis and data statements and "+" and "-" links, along with rules for their use.) The software developer chooses the representational notation and instantiates it as a representational tool, while the user of the tool constructs particular representational *artifacts* in the tool. (For example, in [Fig. 1] the representational artifact is the particular diagram of evidence for competing explanations of mass extinctions.)

Learning interactions include interactions between learners and the representations, between learners and other learners, and between learners and mentors such as teachers or pedagogical software agents. Our 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 guidance**,** expressing certain aspects of one's knowledge better than others do. The concept of representational guidance is borrowed from artificial intelligence, where it is called *representational bias* [Utgoff 1986]. The phrase *guidance* is adopted here to avoid the negative connotation of *bias*. The phrase *knowledge unit* will be used to refer generically to aspects of one's knowledge that one might wish to represent, such as hypotheses, statements of fact, concepts, relationships, rules, etc. The use of this phrase does not signify a commitment to the view that knowledge intrinsically consists of "units," but rather that users of a representational system may choose to denote some aspect of their thinking with a representational proxy. Representational guidance manifests in two major ways:

- *Constraints*: limits on expressiveness, e.g., the representational system may provide a limited ontology of objects and relations [Stenning and Oberlander 1995].
- *Salience:* how the representation facilitates processing of certain knowledge units, possibly at the expense of others [Larkin and Simon 1987].

As depicted in [Fig. 1], representational guidance originates in the notation and is further specified by the design of the tool. It affects the user through both the tool and artifacts constructed in the tool.

2.2 Thesis

The core idea of the theory may now be stated as follows: Representational tools mediate collaborative learning interactions by providing learners with the means to express their emerging knowledge in a persistent medium, inspectable by all participants, where the knowledge then becomes part of the shared context. Representational guidance constrains which knowledge can be expressed in the shared context, and makes some of that knowledge more salient and hence a likely topic of discussion. The following sections clarify this thesis and detail several ways in which constraints and salience are claimed to influence collaborative learning.

2.3 The Origins of Constraints and Salience

Zhang [Zhang 1997] distinguishes *cognitive* and *perceptual* operators in reasoning with representations. Cognitive operations operate on internal representations; while perceptual operations operate on external representations. According to Zhang, the perceptual operations take place without an internal copy being made of the representation (although internal representations may change as a result of these operations). Expressed in terms of Zhang's framework, the present analysis is concerned primarily with perceptual operations on external representations rather than cognitive operations on internal representations. This is because my work is concerned with how representations that reside in learners' perceptually shared context mediate collaborative learning interactions. While cognitive operations on internal representations do influence interactions in the social realm, CSCL system builders do not design internal representations—they design tools for constructing external representations. These external representations are accessed by perceptual operations, so the perceptual features of a representational notation are of interest for CSCL systems.

Stenning and Oberlander [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 my distinction between constraints and salience. *Constraints* are logical and semantic features of the representational notation. *Salience* depends on the perceptual architecture of the agent. Differences in salience can be understood in terms of Zhang's distinction between obtaining information by "direct perception" versus application of perceptual operators. 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.

Zhang's "direct perception" should not be confused with the view that no computation is required for perception. "Direct perception" requires computation, albeit highly automatic and requiring no executive control (e.g., [Triesman and Souther 1987]). Recovery of certain information from a representation may require controlled application of multiple direct perceptions. For example, upon examining a graph, one's perception of the color of a node in a graph is more direct than one's perception of whether this node is connected by links to another specified node [Lohse 1997]. Visual search – a sequence of direct perceptions – is required to make the latter judgement. For our purposes, the important point is that the work required to retrieve any given information from a representation can vary as the representational system changes

2.4 External Representations in Individual and Collaborative Contexts

Substantial research has been conducted concerning the role of external representations (as opposed to mental representations) in individual problem solving. This research generally shows that the kind of external representation used to depict a problem may determine the ease with which the problem is solved [Kotovsky and Simon 1990], [Larkin and Simon 1987], [Novick and Hmelo 1994], [Zhang 1997]. The constraints built into representations may restrict the problem solver's search space, to the possible detriment *or* enhancement of problem-solving success [Amarel 1968], [Hayes 1989], [Klahr and Robinson 1981], [Stenning and Oberlander 1995].

One might ask whether this research is sufficient to predict the effects of representations in collaborative learning.

A related but distinct line of work should be undertaken in collaborative learning contexts for several reasons. The interaction of the cognitive processes of several agents differs from the reasoning of a single agent [Okada and Simon 1997], [Perkins 1993], [Salomon 1993], and therefore 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 guidance. The act of constructing a shared representation may lead to negotiations of meaning that may not occur in the individual case. 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 (Micki Chi, personal communication). Thus it is conceivable that external representations have a greater effect on individual cognition in a social context than they do when working alone. Finally, prior work on the role of external representations in individual problem solving has often used well-defined problems. Further study is needed on ill structured, open-ended problems such as those typical of scientific inquiry.

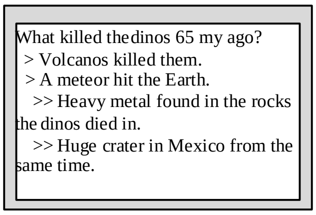
The discussion now turns to the identification of dimensions along which different representational notations vary, and predictions that a given kind of learning interaction will vary along that same dimension.

2.5 Representational Notations Bias Learners Towards Particular Ontologies

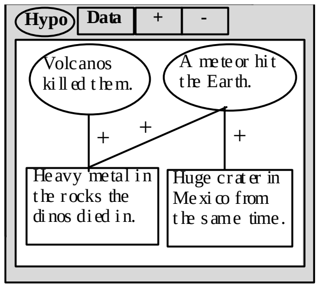
The first hypothesis claims that important guidance for learning interactions comes from ways in which a representational notation *limits* what can be represented [Stenning and Oberlander 1995], [Utgoff 1986]. A representational notation provides a set of primitive elements out of which representational 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 guided to think about the task domain in terms of the underlying ontology.

For example, consider the following interaction in which students were working with a version of Belvédère that required all statements to be categorized as either *data* or *claim*. Belvédère is an "evidence mapping" tool developed under the direction of Alan Lesgold and myself while I was at the University of Pittsburgh [Suthers and Jones 1997], [Suthers et al. 1997], [Suthers and Weiner 1995]. The example is from videotape of students in a 10th grade science class.

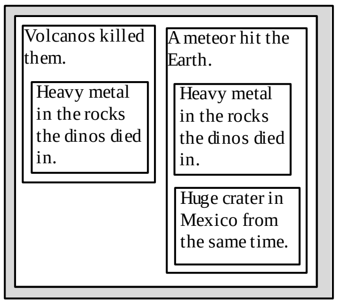
S1: So data, right? This would be data.
S2: I think so.
S1: Or a claim. I don't know if it would be claim or data.
S2: Claim. They have no real hard evidence. Go ahead, claim. I mean who cares? Who cares what they say? Claim.



(a) Threaded Discussion: no representation of relation.



(c) Graph: Relationship as object of perception.



(b) Containment: Implicit representation of relations.

Figure 2: Example of Elaboration Hypothesis

The choice forced by the tool led to a peer-coaching interaction on a distinction that was critically important for how they subsequently handled the statement. The last comment of S2 shows that the relevant epistemological concepts were being discussed, not merely which toolbar icon to press or which shape to use.

2.6 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 and 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. The ability to facilitate learners' elaboration is important because substantial psychological research shows that elaboration leads to positive learning outcomes, including memory for the knowledge unit and understanding of its significance (e.g., [Chi et al. 1989], [Craik and Lockhart 1972], [Stein and Bransford 1979]).

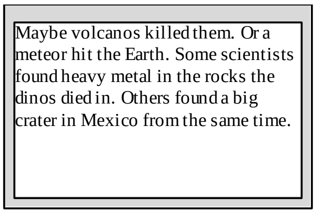
For example, consider the three representations of a relationship between four statements shown in [Fig. 2]. The relationship is one of evidential support. The Containment notation ([Fig. 2]b) uses an implicit device, spatial containment, to represent evidential support, while the Graph notation ([Fig. 2]c) uses an explicit device, an arc. (Also, Graph supports explicit representation of negative relationships, not present in Containment.) 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 [Fig. 2]. Hence the present hypothesis claims that relationships will receive more elaboration in the rightmost representational notation.

An alternative line of thinking leads to a prediction that the elaboration effect may be limited. Learners may see their task as one of putting knowledge units "in their place" in the representational environment. I will call this the *Pigeonhole hypothesis*. For example (according to this hypothesis), once a datum is placed in the appropriate context ([Fig. 2]b) or connected to a hypothesis ([Fig. 2]c), 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 relationships salient.

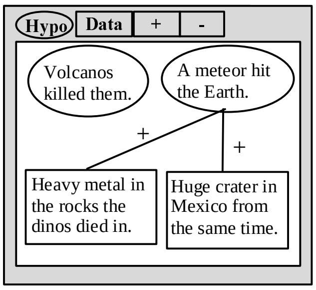
2.7 Salience of Missing Units Guides Search

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, a two dimensional matrix has cells that are intrinsic to the structure of the matrix: they are there whether or not they are filled with content. Learners using a matrix will look for knowledge units to fill the cells.

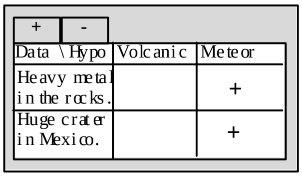
Artifacts from three notations that differ in salience of missing evidential relationships are shown in [Fig. 3]. In the Text representation ([Fig. 3]a), no particular relationships are salient as missing: no particular prediction about search for new knowledge units can be made. In the Graph representation ([Fig. 3]b), 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 one might predict (according to the Pigeon Hole hypothesis) that no further relationships will be sought. The Matrix representation ([Fig. 3]c) has columns for hypotheses and rows for data, with the relationships between these being indicated by symbols "+" or "-" in the cells of the matrix. In the Matrix representation, all undetermined relationships are salient as empty cells. The present hypothesis predicts that learners will be discuss more 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 3: Example of Salient Absence Hypothesis

2.8 Predicted Differences

Based on the discussion of this section, the following predictions were made, and partially tested in the study reported below. The symbol ">" indicates that the discourse phenomenon at the beginning of the list (concept use, elaboration, or search) will occur at a significantly greater rate in the treatment condition(s) on the left of the symbol than in those on the right.

*Concept Use ("*Representational notations bias learners towards particular ontologies*")*: {Graph, Matrix} > {Container, Text, Threaded Discussion}. The Graph and Matrix representations *require* that one categorize statements and relations. This will initiate discussion of the proper choice, possibly including peer coaching on the underlying concepts. The Container, Text, and Threaded Discussion representations provide only implicit categorization. Students may discuss placement of information, but this talk is less likely to be expressed in terms of the underlying concepts.

*Elaboration on Relations ("*Salient knowledge units are elaborated*")*: {Graph, Matrix} > Container > {Text, Threaded Discussion}. Graphs and Matrices make relations explicit as objects that can be pointed to and perceived, while this is not the case in the other two representations. The appearance of one statement inside another's container constitutes a more specific assertion than contiguity of statements in a Threaded Discussion. Hence participants may be more likely to talk about whether a statement has been placed correctly in the Container representation.

*Search for Missing Relations ("*Salience of missing units guides search*"):* Matrix > {Container, Graph} > {Text, Threaded Discussion}. The matrix representation provides an empty field for *every* undetermined relationship, prompting participants to consider all of them. In Graphs or the Container representations, salience of the lack of *some* relationship disappears as soon as a link is drawn to the statement in question or another is placed in its container, respectively. Text and Threaded Discussion do not specifically direct searches toward missing relationships.

The Elaboration hypothesis was not tested independently of the Search hypothesis in this study.

3 An Initial Study

This section reports on an initial study that was conducted to identify trends suggesting that there is a phenomenon worthy of further study; and to refine analytic techniques. Specifically, the study examined how the amount of talk about evidence and the amount of talk about the epistemological status of propositions (empirical versus theoretical) differed across three representational tools, and provided qualitative observations to guide further study.

3.1 Design

Six pairs (twelve participants) were distributed evenly between three treatment conditions in a between-subjects design. The three treatment conditions corresponded to three notations: Text, Graph, and Matrix. These notations differ on more than one feature, such as ontology, whether inconsistency relations are represented, and visual and textual notations. I intentionally chose this research strategy (instead of manipulating precisely one feature at a time) in order to maximize the opportunity to explore the large space of representations within the time scale on which collaborative technology is being adapted.

3.2 Method

3.2.1 Participants

Participants aged 13-14 were recruited by an assistant (Cynthia Liefeld) from soccer practice, and were paid for their participation. All of the participants were male. Two pairs of participants were run in each of the three conditions. Each pair consisted of boys who knew each other, a requirement intended to minimize negotiation of a new interpersonal relationship as a complicating factor.

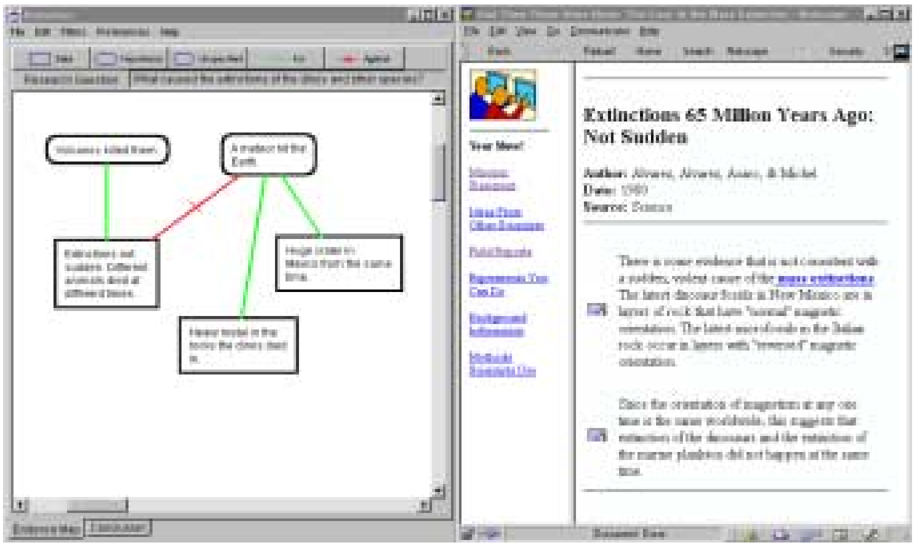


Figure 4: Screen Layout for Studies

3.2.2 Materials

3.2.2.1 Computer Setup

The computer screen was divided in half as shown in [Fig. 4]. The left-hand side contained the representational tool — any one of Text, Graph (shown), or Matrix. The right hand side contained a web browser open to the entry page for the problem.

3.2.2.2 Software

Three existing software packages were used: Microsoft Word (Text), Microsoft Excel (Matrix), and Belvédère (Graph).

Groups using MS Word were free to use it as they wished. We did not restrict participants' appropriation of typographical devices for organizing information, but neither did we encourage any particular use of the textual medium, other than to suggest that they label their statements as *Data* and *Hypotheses* (this was done to make the instructions more similar across groups).

Groups using MS Excel were provided with a prepared matrix that had the labels "Hypotheses" and "Data" in the upper left corner, and cells formatted sufficiently large to allow entry of textual summaries of the same [see Fig. 6]. Participants were specifically told to enter hypotheses as column headers, data as row headers, and to record the relationships in the internal cells.

The Graph condition used Belvédère 2.1 [Suthers and Jones 1997], which provides rounded nodes for hypotheses, rectangles for data, and links for consistency and inconsistency relations between them. Hypothesis and data shapes are filled with textual summaries of the corresponding claims — see the left hand side of [Fig. 4].

3.2.2.3 Science Challenge Problems

Participants were presented with problems in a web-browser (right side of [Fig. 4]). A *science challenge problem* presents a phenomenon to be explained (e.g., determining the cause of the dinosaur extinctions, or of a mysterious disease on Guam known as Guam PD). These are relatively ill-structured problems: at any given point many possible knowledge units may reasonably be considered. The web-based problem materials provided indices to relevant resources, such as lists of articles posing possible explanations of the phenomenon, reporting empirical findings from fieldwork or laboratory work, or explaining basic domain concepts. As shown in [Fig. 4], the materials included summaries of professional journal articles. The materials used in the present study were modified from the classroom versions of science challenge problems developed by Arlene Weiner and Eva Toth. The classroom versions may be viewed at http://lilt.ics.hawaii.edu/belvedere/materials/index.html. The experimental versions excluded hands-on activities, links to external sites and an activity guide. See [Toth et al. 2001] for details on the classroom research.

3.2.3 Procedure

Participants were seated in front of a single monitor and keyboard. After an introduction to the study and signing of permission forms, participants were shown the software and allowed to practice the basic manipulations such as creating and linking nodes or filling in matrix cells. This training did not involve any mention of concepts of evidence or of the problem domain.

Participants were then presented with the problem statement in the web browser on the right. The problem solving session was initiated when they were instructed to identify hypotheses that provide candidate explanations of the phenomenon posed, and to evaluate these hypotheses on the basis of laboratory studies and field reports obtained through the hypertext interface. They were instructed to use the representational tool during the problem solving session to record the information they find and explore how it bears on the problem. Participants were responsible for deciding how to share or divide use of the keyboard and mouse. The procedure described in this paragraph was repeated, first with a "warm-up" problem, and then with the problem for which data is reported below (Guam PD).

Sessions were videotaped with the camera pointed at the screen over the shoulder of one of the participants. The camera was adjusted to show the screen in sufficient detail to see its contents, yet also to show the immediate space around the screen to capture gestures in the vicinity of the screen.

At the conclusion of the problem solving session, participants were asked to write individual essays in which they describe the problem they worked on, any conclusions they reached, the information they used to solve the problem and how they used that information to arrive at their conclusions. Other outcome measures were not attempted because we did not expect learning outcomes after a short treatment time, and because participants were free to browse or ignore the information pages, making it difficult to compare memory for information across individuals.

3.3 Results

Analysis was based primarily on coding of transcripts of participants' spoken discourse, and secondarily on participants' representational artifacts. Each is discussed in turn below. Essay results were inconclusive and are not reported here.

<table>
<tr><td rowspan="3">Representation: Treatment condition.</td><td colspan="2">TEXT: Coded on all segments by MS Word users</td></tr>
<tr><td colspan="2">GRAPH: Coded on all segments by Belvédère Users</td></tr>
<tr><td colspan="2">MATRIX: Coded on all segments by MS Excel users</td></tr>
<tr><td rowspan="8">Topic: The content of participants' utterances or representations.</td><td colspan="2">DOMAIN TALK: Talk about the problem domain, including causality, chronology, constituency, process, spatiality, etc.</td></tr>
<tr><td rowspan="3">Evidential Relation: Discussion or identification of the evidential relationship between two statements.</td><td>CONSISTENCY: Evidential consistency is considered.</td></tr>
<tr><td>INCONSISTENCY: Evidential inconsistency is considered.</td></tr>
<tr><td>EQUIVOCAL EVIDENTIAL: An evidential relation is considered without identifying a particular relation.</td></tr>
<tr><td colspan="2">EPISTEMOLOGICAL CLASSIFICATION: Discussion or identification of the epistemological status of a statement (e.g., empirical, theoretical).</td></tr>
<tr><td rowspan="3">Other Topic: Segments not classified above.</td><td>ON TASK: Segments that are relevant to the problem at hand.</td></tr>
<tr><td>OFF TASK: Segments not relevant to the problem at hand.</td></tr>
<tr><td>UNKNOWN: Segments for which the coder could not determine a category.</td></tr>
<tr><td rowspan="2">Mode: How a statement was made.</td><td colspan="2">VERBAL: Spoken.</td></tr>
<tr><td colspan="2">REPRESENTATIONAL: Modification of the representation.</td></tr>
<tr><td rowspan="2">Level: Terms in which the topic is stated. (Used only for Evidential and Epistemological Classification dimensions.)</td><td colspan="2">CONCEPTUAL: Discussion of questions of evidence or epistemology are in their own terms, e.g., "supports," "explains," "goes against," and "data," "hypothesis".</td></tr>
<tr><td colspan="2">TOOL: Discussion of questions of evidence or epistemology that are stated in terms of the software tool, e.g., "links to"</td></tr>
<tr><td rowspan="2">Ownership: Whether an utterance can be attributed to the participant.</td><td colspan="2">RECITED: Participant was reading materials we provided.</td></tr>
<tr><td colspan="2">NOT RECITED: Participant was not reading materials we provided.</td></tr>
</table>

Table 1: Coding Categories.

3.3.1 Coding and Analysis of Discourse

Videotapes from the six one-hour problem-solving sessions were transcribed and segmented. A segment was defined to be 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 dimensions indicated in [Tab. 1] using the QSR Nud*ist software package. *Italicized* labels in the table are abstract categories: only the SMALL CAPS labels were actually applied to transcript segments.

The *Representation* coding applies uniformly to all segments in any given transcript, and indicates the independent variable for the session (TEXT, GRAPH or MATRIX). The remaining coding is done on a per-segment basis.

Topic provides the primary dependent variables. It divides into two categories (DOMAIN TALK and EPISTEMOLOGICAL CLASSIFICATION) and two sub-dimensions of categories (*Evidential Relation* and *Other Topic*).

Topic category DOMAIN TALK codes discourse about the problem domain (e.g., "See if they are close to each other," "They get it from the rivers," "Maybe they don't soak it long enough"). Topic category EPISTEMOLOGICAL CLASSIFICATION codes discourse about the epistemological status of a statement, including classification as empirical (e.g., "that's data"), theoretical (e.g., "that's a hypothesis, isn't it?") or discussion of the choice (e.g., "do you want me to go data or hypothesis?"). In subsequent work, EPISTEMOLOGICAL CLASSIFICATION will be subdivided into Theoretical, Empirical, and Equivocal, in a manner similar to *Evidential Relation* (discussed below). In the present study I only wanted to see whether the tools differed in their prompting for making this choice. To avoid confusion it should be noted that this code is *not* applied to statements of hypotheses or data themselves: only explicit discussion of whether statements belong to one of these categories.

Topic sub-dimension *Evidential Relation* is applied to segments where participants discuss or identify the nature of the evidential relationship between two statements. The codes are CONSISTENCY (e.g., "it's also for," "that confirms"), INCONSISTENCY ("so that's against," "with this one, no, conflicts, right?"), or EQUIVOCAL, applied when participants raise the question of which relationship holds, if any, without identifying one specifically ("is that for or against?," "it can neither confirm nor deny"). In some cases, evidential relationships were apparently being expressed in terms of the representational primitives provided by the software (e.g., "connect these two"). These utterances were also coded with the appropriate *Evidential Relation* category, but marked with the *Level* code (discussed below) so that such tool-level talk could be distinguished during the analysis.

Topic sub-dimension *Other Topic* codes segments not coded as one of the above topics. The codes include ON-TASK (e.g., "are we done with this?"), OFF-TASK (e.g., "what's for lunch?"), or UNCLASSIFIABLE (e.g., "uh," mumbles, etc.).

The remaining coding dimensions are used to select out relevant segments for particular analyses. *Mode* indicates whether the segment is coded for its VERBAL content or for an action taken on the REPRESENTATIONAL artifact. The final two dimensions only apply to verbal segments. *Level* is applied only to VERBAL EPISTEMOLOGICAL CLASSIFICATION and EVIDENTIAL RELATION segments, and indicates whether an utterance made direct use of epistemological or evidential concepts (e.g., "supports," "hypothesis": CONCEPTUAL) or was expressed in terms of the software (e.g., "link to this," "round box": TOOL-BASED). *Ownership* indicates whether the participant was merely reading text that we provided (RECITED) or making one's own contribution (NON-RECITED).

Verbal segments tested: nesting indicates subset selection; % are of "Not Off-Task"	**Text**		**Graph**		**Matrix**	
	N	***%***	***N***	***%***	***N***	***%***
Non-Recited	778	*n/a*	626	*n/a*	537	*n/a*
..Not Off-Task	694	100	613	100	508	100
….Evidential Relation	4	0.58	32	5.22	100	19.69
……Consistency	3	0.43	21	3.43	54	10.63
……Inconsistency	1	0.14	6	0.98	35	6.89
……Equivocal Evidential	0	0.00	5	0.82	11	2.17
……Conceptual	3	0.4	9	1.47	43	8.46
……Tool-Based	1	0.1	23	3.75	57	11.22
….Epistemological Classification	39	5.62	57	9.30	36	7.09
……Conceptual	19	2.74	33	5.38	7	1.38
……Tool-Based	20	2.88	24	3.92	29	5.71

Table 2: Summary of Verbal Coding

Coding was performed by two of my assistants (Chris Hundhausen and Laura Girardeau). Questions of interpretation, problematic segments, etc. were discussed among the three of us during meetings, but the coding itself was done independently. Inter-rater reliability was computed using the Kappa statistic across all of the categories described above, producing a value of 0.92 (n=1942).

Selected results of coding are shown in [Tab. 2], focusing on segments coded as Mode=VERBAL, and showing both counts and percentages for each of the three treatment groups. Percentages are taken relative to NON-RECITED on task utterances, shown in the second row. Counts and percentages for EVIDENTIAL RELATION are broken down in two orthogonal ways: by whether the relation was CONSISTENCY, INCONSISTENCY, or EQUIVOCAL; and by whether the talk about evidence was CONCEPTUAL or TOOL-BASED. EPISTEMOLOGICAL CLASSIFICATION was broken down by CONCEPTUAL or TOOL-BASED. Due to the small sample size we did not perform statistical testing.

3.3.2 Qualitative Observations

The document created by one TEXT group contained no expression of evidential relations [see Tab. 3], and the transcript of verbal discourse for this group contained no overt discussion of evidential relations. We did observe an effect of the representation on participants' discourse: discussion of spelling was prompted by MS Word's red underlining of unrecognized words [Tab. 4]. All of the discussion of evidence in TEXT occurred in the other group at the end of the session (the longest session in the pilot study). This group had run over time in their session. The experimenter was concerned that the participants' mothers were waiting, so prompted the participants to draw their conclusions. All of the talk about evidence took place in response to this prompt. This second group's document was substantially more verbose than that of the first group shown in [Tab. 3].

Research Question: What is the mysterious muscle and mind killer?
H1: It could have come from the water.
H2: Somebody could have put it in the water.
Data1: The scientists believe fadang didnt cause it.
Data 2: When you get the disease you hands feel numb One mans wife got it and she feels numbness through her whole body she can still move parts of her body but not her feet
Data 3: There is a mineral imbalance in the water.
Data 4: An unusual amino acid has been isolated in chickling peas in the area.

Table 3: Sample Text Document

L:	Okay, um, scientists don't believe that fadang is a, is the cause of the virus.
R:	Believe what? Believe what?
L:	Fadang didn't cause it. <typing> F-A-D-A-N-G
R:	Mmm.
L:	What?
R:	Nothing. You spelled it wrong.
L:	<clicks> What is it, 'A'?
R:	Yeah. <mumble> It's still wrong.
L:	No it isn't.
R:	Yes it is. Then why is it, why is it underlined with the x thing? <points to l-hand side of screen>
L:	Not wrong.

Table 4: Text Transcript Sample

A document produced by one of the GRAPH groups is shown in [Fig. 5]. This graph is somewhat linear, in spite of the fact that graphs are normally considered a nonlinear medium. A pattern of *identify information, categorize information, add it to the diagram, link it in* is typical of interactions in this transcript [see Tab. 5]. This pattern of activity, which leads to the linearity of the graph, is consistent with the Pigeonhole Hypothesis: participants may feel that the primary task is to connect each new statement to something else, after which it can be ignored.

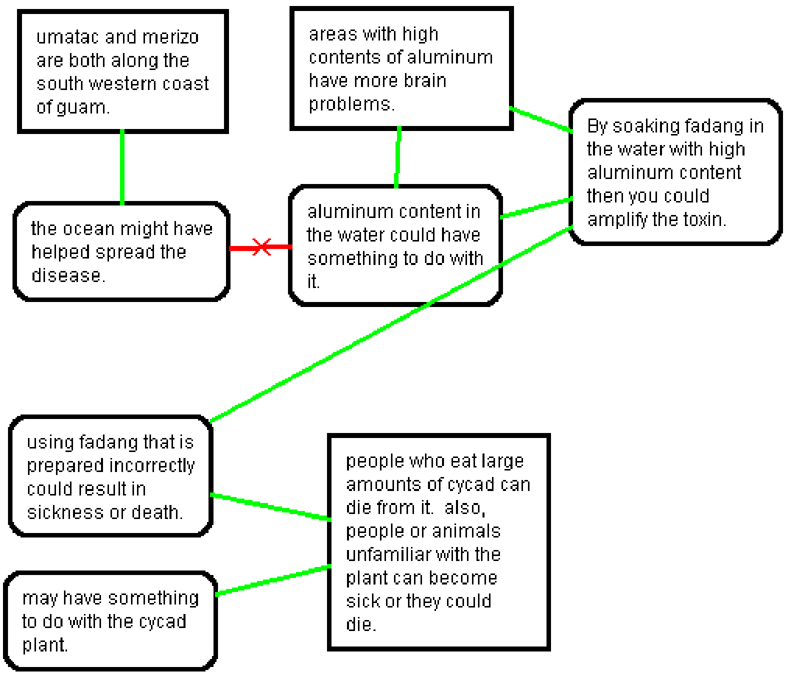


Figure 5: Graph Artifact

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 "using fadang that is prepared incorrectly could result in sickness or death">
L:	What if they don't prepare it right?
R:	Right
L:	Oops
R:	Okay, huh?
L:	<mumble>
R:	<mumble>, this? add to our investigation?
L:	Yeah, add to investigation <adding link to "By soaking fadang ...">; and that also goes to cycad, too
R:	Well, wait, uh
L:	Hold over <adding link to "people who eat large amounts of cycad ...">
R:	And this stuff is the same thing as fadang, right?
L:	Yeah

Table 5: Graph Transcript Sample

Research Question: What causes neurological 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	Radiation temporarily contaminated the food of the South pacific
nutritionist claims that chamorros, found in FADANG, killed several people	confirm	conflict	confirm	conflict	confirms
Nutritionist claims that lack of Calcium in Pacific region causes brain desease	conflict	conflict	confirm	conflict	conflicts
spinal/brain disfunctions causing desease	conflict	conflict	conflict	confirm	conflicts
Certain Amino Acids found in food (peas) cause disfunction in the brain	confirms	conflicts	confirms	confirms	confirms
Test between 1941-1945 proved that all patients in the hospital were Chamorro and had ALS	confirms	conflicts	confirms	confirms	confirms
The same test run now proved that there's a major decline in the rate of Als found in Guamian	confirms	confirms	conflicts	confirms	confirm

Figure 6: Matrix Artifact

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 2nd hypothesis in table> one because it has had nothing but conflicts. The Hiroshima ...that we thought of ourselves.
R: It conflicts, conflicts, conflicts. It hasn't had one, uh...

Table 6: Matrix Transcript Sample

Finally, the MATRIX artifacts were especially striking because participants were not specifically instructed to fill in all the cells, yet they did so [see Fig. 6]. The transcripts illustrated participants' systematic identification of evidential relations as they worked down the columns, and in one case their appropriate use of the table to rule out a hypothesis that they had proposed. Both of these points are illustrated in the transcript segment of [Tab. 6].

3.4 Discussion

Recall that the Search hypothesis predicts that participants will be more likely to seek evidential relations when using representations that prompt for these relations with empty structure (TEXT < GRAPH < MATRIX). The [Tab. 2] row labeled "EVIDENTIAL RELATION" is relevant to the Search hypothesis. This row counts, for each treatment group, the percentage of verbal segments that were coded with any one of the three evidential values (CONSISTENT, INCONSISTENT, EQUIVOCAL). The results are consistent with the Search hypothesis: TEXT=0.58% < GRAPH=5.22% < MATRIX=19.69%. This trend holds even when limited to CONCEPTUAL expressions of evidential relations: TEXT=0.43% < GRAPH=1.47% < MATRIX=8.48%. Note however that a substantial portion of talk about evidence in the GRAPH and MATRIX conditions is tool based (about two-thirds of Graph and half of Matrix evidential utterances are TOOL-BASED). This is as expected, since these tools, unlike TEXT, provide objects that may be referred to as proxies for evidential relations.

The breakdown of evidential talk according to the type of relation shows the influence of the exhaustive prompting of MATRIX. In TEXT and GRAPH, participants focused primarily on CONSISTENCY relations, a possible manifestation of the confirmation bias [Klayman and Ha 1987]. Treatment was more balanced in MATRIX, with almost half of the talk about evidential relations being concerned with inconsistency or equivocal relations. This may be because MATRIX prompts for consideration of relationships between all pairs of items: participants are more likely to encounter inconsistency or indeterminate relations when considering pairs that others may have neglected in the GRAPH or TEXT conditions.

Turning to EPISTEMOLOGICAL CLASSIFICATION, the difference between TEXT and MATRIX was not as strong as expected. The ontological prompting of MATRIX may be obscured by the fact that the instructions for all three conditions directed participants to consider and record hypotheses and empirical evidence. TEXT participants, like others, complied with these instructions, for example labeling propositions as "Data" or Hypothesis" in the document reproduced in [Tab. 3]. However, the GRAPH condition shows a greater proportion of epistemological classification talk. This is expected because of GRAPH'S use of visually distinct shapes to represent data and hypotheses.

Overall, the results are encouraging with respect to the question of whether there is a phenomenon worth investigating. Differences in the predicted directions were seen in both talk about evidence and about the epistemological status of statements. However, 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 a learning outcomes measure, and the need for a more direct test of the claim that representational state affects subsequent discourse processes.

Furthermore, analyses 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. For example, one might code changes to the representations 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 that time-window could be tested for either (a) elaboration on those knowledge units or (b) search for other knowledge units related by evidential relations. This would provide a more stringent test of the causal relationship between salience and discourse claimed by the research hypotheses.

All of these issues are being addressed in a study underway at this writing. The study involves a larger sample size and learning outcome measures, as well as a more controlled presentation of materials. Instead of commercial software, we are using versions of Belvédère that have been modified to provide the alternative representations in [Fig. 3], in order to reduce nonessential differences between the representational tools and enable automated recording of all manipulations of the representations in log files. Initial results, to be reported in future publications, show effects on discourse processes similar to the results reported here. See also [Toth et al. 2001] for a classroom study with consistent results based on an analysis of artifacts created by students during a two-week project. Plans for future work include attempts to replicate selected experimental results in distance learning situations, both synchronous and asynchronous, as well as further classroom work.

4 Summary

This paper introduced the hypothesis that variation in features of representational tools could have a significant effect on the learners' knowledge-building discourse. I sketched a theoretical analysis of the role of constraints and salience in representational guidance, and reported results from the first in a series of investigations. The study suggests that appropriate representational guidance may result in increased consideration of evidential relations by collaborating learners. Further work is needed to provide more stringent testing of the hypotheses and to situate results in terms of possible learning outcomes. This line of work promises to inform the design of future software learning environments and to provide a better theoretical understanding of the role of representations in guiding group learning processes.

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