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Representational Guidance for Collaborative Learning

Daniel D. Suthers
Dept. of Information and Computer Sciences, University of Hawai'i at Manoa
suthers@hawaii.edu

Abstract. When people engage in conversations for learning or problem solving, they often reference and manipulate external (visual and textual) representations. Online, external representations take on additional importance because they are also the medium of communication. In this paper I highlight a few important aspects of the roles that external representations can play in the meaning-making activities of two or more participants, and how the particular representation used may influence these activities. I will draw upon my own research for examples. One line of work showed how the properties of representations used to support evidence-based inquiry can affect both discourse activities and student work. A second line of work showed that the distinction between communication tools and other representations is blurred online, with the actual discourse between participants being accomplished by actions in all of the mutable representations. These phenomena are unified by the concept of representational guidance: the constraints, visual properties, and conventions of use associated with representations should be considered in designing to guide learning activities.

1 Introduction

In a previous publication in this conference (Suthers, 1999) I outlined a research agenda intended to expose the ways in which features of external representations can guide collaborative learning interactions. The present paper is a progress report of that work to the AI&ED community, summarizing highlights of four years of research.

Comparisons of alternate representations for problem solving and learning has been fundamental to artificial intelligence at least since the classic paper by Amarel (1968), which demonstrated a dramatic simplification of the "missionaries and cannibals" problem by transforming representations of the problem space. Utgoff (1986) showed how the choice of representation for concepts could bias a machine-learning algorithm by limiting the search space, with desirable or detrimental results depending on whether the target concept could be represented in the constrained language. Utgoff termed the effect "representational bias," which I have adapted as "representational guidance" to make the phrase more palatable to the sensitive educator.

Studies of human problem solving also show the critical importance of choice of problem representation (Kotovsky & Simon, 1990; Larkin & Simon, 1987; Novick & Hmelo, 1994; Zhang, 1997). In general, the representational system provided to problem solvers can have a dramatic influence on their ability to solve a problem and the time taken to solve it. Results such as these have led to work on the choice of representations for learning applications, including providing learners with representations that help them see the problem and solution structure (e.g., Koedinger, 1991) and helping learners choose an appropriate representation or manage multiple representations (van Someren, Reimann, Boshuizen, & de Jong, 1998).

Inspired by informal observations of students collaborating with Belvedere (Suthers & Weiner, 1995) as well as Roschelle's (1994) article on "mediating collaborative inquiry" and Collins & Ferguson's (1993) concept of "epistemic forms," I posed the question of whether representations might differentially influence *collaborative* learning in ways relevant for design. Did it matter that some collaborative inquiry projects were using threaded discussion and others a container representation while Belvedere used graphs? In collaborative learning, we would expect the effects on individuals (such as those just cited) would aggregate to influence group performance, but I suspected that this was only part of the story. I hypothesized that additional forms of representational guidance might emerge from the shared use of representations by distributed cognitions (Salomon, 1993). Over time, I identified three roles of external representations that are unique to situations in which a group is constructing and manipulating shared representations as part of a constructive activity.

1. *Initiating negotiations of meaning.* An individual who wishes to add to or modify a shared representation may feel some obligation to obtain agreement from one's group members, leading to negotiations about and justifications of representational acts. This discourse will include negotiations of meaning and shared belief that would not be necessary in the individual case, where one can simply change the representation as one wishes. The creative acts afforded by a given representational notation may therefore affect which negotiations of meaning and belief take place.

2. *Supporting conversations through deixis.* The components of a collaboratively constructed representation, having arisen from negotiations of the type just discussed, evoke in the minds of the participants rich meanings beyond that which external observers might be able to discern by inspection of the representations alone. These components can serve as an easy way to refer to ideas previously developed, this reference being accomplished by gestural deixis (reference to an entity relative to the context of discourse by pointing) rather than verbal descriptions (Clark & Brennan, 1991). In this manner, collaboratively constructed external representations facilitate subsequent negotiations, increasing the conceptual complexity that can be handled in group interactions and facilitating elaboration on previously represented information.

3. *Reminder of common ground.* The shared representation also serves as a group memory, reminding the participants of previous ideas (encouraging elaboration on them) and possibly serving as an agenda for further work. Individual work also benefits from an external memory, but in the group case there is an additional awareness that one's interlocutors may be reminded by the representation of prior ideas, prompting oneself to consider potential commentary that others will have on one's proposals. That is, it becomes harder to ignore implications of prior ideas if one is implicitly aware that one's interlocutors may also be reminded of them by the representations (Michelene Chi, personal communication). This function of representations can invoke the first function: negotiations of meaning.

The fundamental hypothesis of this work is that external representations fill these roles in different ways according to their representational guidance: The potential actions afforded by a representational notation may influence what is negotiated: it constrains what might be expressed and makes certain constructive activities (ways in which the representational artifact could be extended) more salient than others (Stenning & Oberlander, 1995). The deictic value of a representation will be constrained by what is represented and be influenced by what is salient and hence easily referenced through gesture. Similar considerations apply to implicit reminding of common ground.

Based on an earlier version of this reasoning, my 1999 paper made predictions about several classes of representations (text, container, graph, matrix) along three dimensions of effects: (1) that the representations would influence the ontology participants use in discussing a problem; (2) that the representations would differ in how much they prompt for consideration of evidential relations; and (3) that they would differ in how much participants elaborate on information once it is represented. In the remainder of the paper I summarize my research that addressed these and other related hypotheses.

2 A Summary of the Research

A series of studies were undertaken with various versions of Belvedere (Suthers et al., 2001) to test the effects of selected representations on collaborative inquiry. These studies include a formal classroom study and formal laboratory studies. The classroom study provided evidence that representational guidance influences students' work in "natural" settings. For logistical reasons (the classrooms were overseas) we were only able to observe students' work products in the classroom study. The laboratory studies provided a closer look at the effects of representational guidance on learning *processes* under controlled conditions, with a particular focus on the predictions just stated.

2.1 Guidance for Inquiry in a Classroom Setting

Eva Toth, Arlene Weiner and I developed a comprehensive method for implementing Belvedere-supported collaborative inquiry in the classroom. Students work in teams to investigate "science challenge problems" that present a phenomenon to be explained, along with indices to relevant resources. The teams plan their investigation, perform hands-on experiments, analyze their results, and report their conclusions to others. Investigator roles are rotated between hands-on experiments, tabletop data analysis, computer-based literature review, and use of modeling tools such as Belvedere. Assessment rubrics are given to the students at the beginning of their project as criteria to guide their activities. The rubrics guide peer review, and help the teacher assess non-traditional learning objectives. See Suthers, Toth & Weiner (1997) or Toth, Suthers & Lesgold (2002) for further information on this integrated approach to classroom implementation.

As part of this work, we conducted a classroom study comparing two forms of guidance for inquiry with respect to quality of inquiry process and conclusions (Toth et al., 2002). The forms of guidance included Belvedere's graphical representations of evidential relations, and assessment rubrics. The Belvedere graphs relate data and hypothesis objects (represented by distinct shapes) with consistency and inconsistency relations (represented by links labeled "+" and "-"). The assessment rubrics were paper-based charts that included detailed criteria, in Likert-scale format, for progress in data collection, evaluation of information collected, quality of reports, and quality of peer presentations. The rubrics were provided to students at the outset of the study with explicit instructions to use them during the activity to guide inquiry. A 2x2 design crossed Graph (Belvedere) versus Text (Microsoft Word) conditions with Rubric versus No-rubric conditions across four 9^{th} grade science classes. Students spent about 2 weeks on each of three science challenge problems.

The data analysis was based primarily on artifacts produced by groups of students, namely their Belvedere graphs or Word documents, and their final report essays. The amount of information recorded did not differ significantly between groups. Significant results were obtained on the categorization of information and the number of evidential relationships recorded. Specifically, the Graph groups recorded significantly more evidential relations than the Text groups, and the Rubrics users recorded significantly more evidential relations than those groups who did not use the rubrics for explicit reflection. An interaction between the type of representational tool and the use of rubrics prompted a post-hoc comparison. We found that the combination of graphing and rubrics resulted in a larger number of evidential relations recorded compared to all other conditions; while the use of either graphing or rubrics alone did not result in significant difference. Further analysis showed that this interaction was primarily due to the Graph/Rubrics students having recorded significantly more inconsistency relations. Thus, there appears to be a synergistic effect between effective representations and guidelines for their use, particularly with respect to attending to discrepant evidence. The best results were obtained with the combination of rubrics encouraging students to look for and record disconfirming as well as confirming information and explicit representational devices for recording such inferences.

2.2 Comparing Three Representations in a Laboratory Setting

Subsequent laboratory studies were undertaken to observe representational guidance of argumentation processes that were not accessible to us in the trans-Atlantic classroom study. With the capable assistance of Christopher Hundhausen and Laura Girardeau, I conducted a study comparing three alternative notations for recording evidential relationships between data and hypotheses (text, graphs, and matrices) with respect to participants' amount of talk about evidential relations (Suthers & Hundhausen, 2003). We employed a single-factor, between-subjects design with three participant groups defined by the notation they used. Dependent measures included: (a) categorization of utterances and participant actions in the software; (b) ability to recall the data, hypotheses, and evidential relations explored in a multiple-choice test; and (c) ability to identify, in a written essay, the important evidential relations between the data and hypotheses presented.

Sixty students were recruited out of introductory science courses in self-selected, same gender pairs, Participant pairs were randomly assigned to the three treatment groups. Participant pairs worked with software with two main windows, one containing a workspace for creating either text, graph, or matrix representations, and the other presenting a science problem (what causes a mysterious neurological disease in Guam?) as a fixed sequence of 15 information pages. Participants were instructed to visit each page in the sequence, and to record data, hypotheses, and evidential relations. Once finished, they were individually given a post-test, and then asked to work together on an essay summarizing their findings.

All 30 sessions were videotaped and transcribed, including both verbal utterances and actions performed with the software. Transcript segments were coded on several dimensions, including content categories such as whether participants were discussing issues of evidence or using empirical or theoretical concepts. Essays were scored according to the strength and inferential difficulty of the evidential relations they cited.

We found significant differences with respect to overall percentages of evidential relations segments, and with respect to the percentages of verbal evidential relations segments. A post-hoc test determined that, in both cases, the significant differences were between Matrix and Graph and between Matrix and Text. These results confirmed our prediction that notation significantly impacts learners' discussion of evidential relations. The data on ontological bias was inconclusive. In order to provide equivalent instructions to all groups, the instructions provided to Text users modelled labelling of sentences with "Data" and "Hypothesis." Apparently participants faithfully complied with these instructions, leading to just as much use of these concepts in Text as in the other groups.

Further analyses of the same data focused on the contents of participants' representations and their elaborations on (revisitations and reuse of) information and beliefs once they are represented. The results of these analyses indicated that visually structured and constrained representations provide guidance that is not afforded by plain text. Users of Matrix and Graph revisited previously discussed ideas more often than users of Text, as was predicted from the greater salience of ideas and prompting for missing relations in the more structured representations. However, not all guidance is equal, and more prompting is not necessarily better. Comparison of participants' represented content to our own analysis of the problem domain indicated that Text and Matrix users represented more hypotheses and Matrix users represented far more evidential relations than can be considered relevant by our analysis. Matrix users revisited prior data and hypotheses mainly to fill in the matrix cells that relate them. They revisited relations far more often than Text or Graph users, but often appeared to be doing this because they are attempting to make relationships between weakly or equivocally related items due to the exhaustive prompting of the matrix. A representation such as Graph may guide students to consider evidence without making them unfocused.

We found no significant differences between the groups' post-test scores (recognition of factual information) and essay scores (using various measures of quality of inference), although all trends were in the predicted direction. These results were disappointing, but not surprising. Participants spent less than an hour on task, and this may not have been enough time for learning outcomes to develop fully. We did find that the contents of the graph representations overlapped with the content of those participants' essays more than the corresponding representations overlapped in the text or matrix conditions. This result suggests that the work done using graphs had more relevance for participants' views of the problem. Yet we cannot rule out the possibility that representational effects on learning processes might not translate to differences on traditional learning outcomes measures.

2.3 The Roles of Representations in Face-to-Face and Online Collaboration

All of the foregoing studies were undertaken with face-to-face collaboration of participants, yet online learning is becoming increasingly important, especially in higher education. We conducted a follow-up study designed to explore how the roles of representations in online learning might shift, with possible implications for the relevance of representational guidance (Suthers, Hundhausen & Girardeau, submitted). Although my strongest interest is in asynchronous learning environments, we studied synchronous online collaboration so that we could compare online discourse to our synchronous face-to-face data. This study was undertaken with a version of the Belvedere 3.0 research software that supported synchronous computer-mediated communication (CMC) with a textual "chat" provided in addition to the graph representation and information pages.

There are of course many variables of interest in CMC and a large literature. Studies of synchronous problem solving generally show degradation of both problem solving performance and interpersonal communication due to the reduced "bandwidth" or available modes of interaction associated with technology-mediated communication (Olson & Olson, 1997; Doerry, 1996), although factors extrinsic to the technology itself may play a role (Walther, 1994). However, an extensive literature on asynchronous online learning typically concludes that there is no significant difference in learning outcomes as compared to traditional classroom learning (Russell, 1999). It was not our intent to replicate these results: our focus was on how the roles of external representations in supporting collaboration might change when going online, especially in ways that might affect the relevance of representational guidance.

We conducted sessions with 10 pairs of students using the CMC version of Belvedere 3.0, and compared these sessions to the face-to-face graph sessions from the previous study in order to identify how the roles of representations in supporting collaboration might change. Two hypotheses were considered without prejudice:

(H1) Visual knowledge representations will play less of a role in guiding discourse online because without co-presence the representations do not as easily function to convey "taken as shared" information or support deixis.

(H2) Visual knowledge representations will play a greater role in supporting discourse online because participants will make use of them to make up for the reduced bandwidth of the verbal modes of interaction.

Our quantitative results provided adequate evidence for the second hypothesis. In the online condition, there was a clear shift to a greater number of communicative acts being undertaken in the graphical knowledge representation as opposed to spoken or chat communications. We found an increased focus on categories supported by the software (i.e., evidential relations and epistemic classifications). We also observed a shift in the role of the graph representation from object of discourse in the face-to-face condition to medium of discourse in the CMC condition. Online participants introduce new ideas directly in the graph medium (rather than in the chat) far more often than face-to-face participants, who always introduced and discussed new ideas verbally before modifying the graph representation.

However, there was also qualitative evidence for the first hypothesis. Our informal review of the transcripts shows many examples of poorly coordinated activity in the online groups, such as disconnects between the activity in the workspace and the verbal activity in the chat. The two hypotheses are not in direct conflict, and may be synthesized as follows: Lack of mutual awareness of orientation towards shared representations may result in poorer coordination of immediate activity and the thinking behind it (H1). At the same time, greater reliance may be placed on those very representations as the medium *through* which activity takes place, biasing activity towards actions best supported by the representations (H2).

From this work we learned that online discourse will not be confined to the medium provided for natural language interaction: it will be distributed across all mutable representations and influenced by the properties of those representations. Therefore, close attention must be paid to the design of affordances for argumentation in *all* representations provided to online collaborators.

3 Related and Future Research

During this time, other researchers have undertaken related studies using or inspired by Belvedere. Veerman (2003) compared Allaire Forums (asynchronous online discussion), Belvedere 2.0 (using synchronous discussion with a chat tool) and NetMeeting in a heterogeneous design (the activities were not identical). Among other differences, they observed a greater percentage of argumentation related content, particularly counter-arguments, in Belvedere, a result that seems consistent with the Toth et al. (2002) result on discrepant evidence. Schwartz, Neuman, Gil, & Ilya (2002) showed that argument maps were superior to pro-con tables in supporting students' collaborative argumentation and essay writing, but these differences were not internalized individually during the relatively short study. Other direct comparisons of alternate representations in collaborative learning are rare, but see Baker and Lund (1997) and Guzdial, et al. (1997).

Further work is needed to develop a generalized understanding of representational guidance for collaborative learning. Follow-up studies within the experimental paradigm could investigate whether similar representational effects on collaboration are obtained in different task domains (those that offer multiple representations are of particular interest), with different learning or problem solving objectives, and with other populations. Studies in other research paradigms should be undertaken to investigate how learners' use of representations develops over time in authentic inquiry settings, and to explore whether the choice of representational notation also influences collaborative learning processes after extended use.

4 Conclusions

The studies of representational guidance for collaborative learning summarized in this paper were motivated by the idea that some roles of representations in supporting learning are endemic to collaborative situations and that logical and perceptual differences between representations may influence how they fill these roles. A laboratory study confirmed several predicted process differences, including discussion of evidence and revisitation of prior information, as well as suggestive results indicating that the work done with graphs had greatest impact on participants' understanding of the problem. A study of the products of students' classroom work showed similar effects of representation on consideration of discrepant evidence, this effect being amplified by a coordinated set of peer-evaluation rubrics calling for evaluation of discrepant evidence. The online study showed that all actionable/mutable representations will be appropriated as part of the discourse medium (not just the intended discussion tools); and therefore we may expect representational guidance to be enhanced in online discourse.

The immediate implication of this work is that system designers should treat representational design as design of resources for conversation between learning agents (Roschelle, 1994). A designer might ask: What activities does a given representational notation suggest or prompt for? Do the actions that can be performed on a shared representation in this notation correspond to the potential ideas that we want collaborators to negotiate and distinctions we want them to attend to? Do the resulting representations express and make salient the ideas and relationships that collaborators should revisit and relate to new information? Are the needs that should be addressed by subsequent activity, such the lack of information, made obvious? Do the representations capture important aspects of learners' thinking and expose conflicts between alternative solutions or perspectives? Stepping beyond the scope of the studies reported here, does the notation provide the preferred vocabularies and representational perspectives that constitute both the target skill to be learned as an aspiring member of a community and focus learning activity on ways of approaching a problem that are productive? Representational notations are not determinants of behavior, but when the features of representations are coordinated with the design of other elements of a learning situation they can guide behavior.

This line of work underlines a broader point: the importance of designing with the whole human-computer system in mind. Activity theory (Engeström, 1987) tells us that tools and artifacts (among other things) mediate the influences of various learning resources (such as other individuals, community norms, and roles) on the learner. Therefore, the impact of the representational choices we make in designing these tools is not limited merely to the direct effects of representations. The impact of these choices will be amplified to the extent that the representations mediate how other resources in the human-computer system bear upon the learning activity.

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