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Co-Lab: research and development of an online learning environment for collaborative scientific discovery learning

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Abstract

There are many design challenges that must be addressed in the development of collaborative scientific discovery learning environments. This contribution presents an overview of how these challenges were addressed within Co-Lab, a collaborative learning environment in which groups of learners can experiment through simulations and remote laboratories, and express acquired understanding in a runnable computer model. Co-Lab's architecture is introduced and explicated from the perspective of addressing typical problem areas for students within collaborative discovery learning. From this view the processes of collaboration, inquiry, and modeling are presented with a description of how they have been supported in the past and how they are supported within Co-Lab's design and tools. Finally, a research agenda is proposed for collaborative discovery learning with the Co-Lab environment.

Keywords: Collaborative learning; Inquiry learning; Learning environments; Dynamic modeling

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1. Introduction

Socio-constructivist learning theories perceive learning as a constructive, situated and collaborative process. These theories converge on the notion that learners develop understanding of a domain by working on authentic tasks in realistic settings. Task performance preferably occurs in collaboration with peers, and should be regulated by the learners (instead of the teacher or the learning material).

In science education, these notions of learning can be implemented by letting learners "act like scientists". That is, learners should perform experiments to discover relationships between phenomena, and construct models to express their understanding. Clearly, these learning activities are more constructive by nature than, for instance, listening to lectures or solving paper-and-pencil physics problems. Experimentation and modeling are also authentic activities that reflect the way scientists go about in studying unknown phenomena. Learners thus develop domain knowledge and, at the same time, familiarize themselves with a scientist's way of working and thinking (cf. Brown, Collins, & Duguid, 1989). Such enculturation can be further enhanced through collaboration. Teamwork has long since been a common practice in science and many scientific discoveries were a joint effort (Dunbar, 2001).

Organizing science education around collaborative inquiry and modeling activities requires innovative, student-centered forms of instructional support. Collaborative discovery learning environments are a potentially powerful means to offer this type of support, provided that their design meets certain criteria. One obvious demand concerns the presence of tools learners can use to explore a task domain through experimentation. Yet merely doing experiments does not capture the full range of scientists' activities, nor will it develop deeply rooted, transferable knowledge and skills. Structural changes in domain knowledge require reflection in conjunction with modeling, and reflection is a natural component of the social interaction that occurs in collaboration (Penner, 2001). Collaborative discovery learning environments should therefore comprise tools that support inquiry through experimentation, domain modeling and student collaboration.

This article exemplifies how this type of support might be brought about. It does so by articulating the design considerations for Co-Lab, a learning environment in which groups of learners can experiment through simulations and remote laboratories, and express acquired understanding in a runnable computer model. The next section presents an overview of Co-Lab's basic architecture. The sections that follow elucidate how the processes of inquiry, modeling and collaboration are supported within the environment and its tools. In the final section, a research agenda is proposed for collaborative discovery learning with the Co-Lab learning environment.

2. The structure of Co-Lab learning environments

Co-Lab supports collaborative discovery learning in the natural sciences at the upper secondary level and the first years in university. Content is currently available for four domains: water management, greenhouse effect, mechanics and electricity. Water management and greenhouse effect are extensive courses that cover the richness of these interdisciplinary domains. Both courses comprise several modules of different levels of complexity.

A building metaphor was used to elucidate this multi-level structure. Learners have access to one or more buildings symbolizing the courses in the various domains. Each building contains multiple floors (representing the modules) and each floor has multiple rooms to structure the learners' activities. Experimenting and modeling are supported in the Lab and Theory room, respectively. The Meeting room is intended for planning and monitoring; the Hall is where learners gather and collect their assignment. Buildings and floors thus organize the domain, rooms organize the learning activities.

Fig. 1 shows the Co-Lab interface that appears upon entering a floor. The top-right part of the screen is the main working area. Here students can select various tools for experimentation and modeling. In keeping with the building metaphor, different tools are available in different rooms, so the content of this part of the screen depends on the learner's current location.

The left-hand side of the screen houses generic tools for navigation and collaboration as well as a tool to move learning objects across rooms. This part of the screen remains unchanged when students switch rooms, making its tools available in all rooms. The same is true for the bottom part of the screen where a synchronized chat tool supports communication.

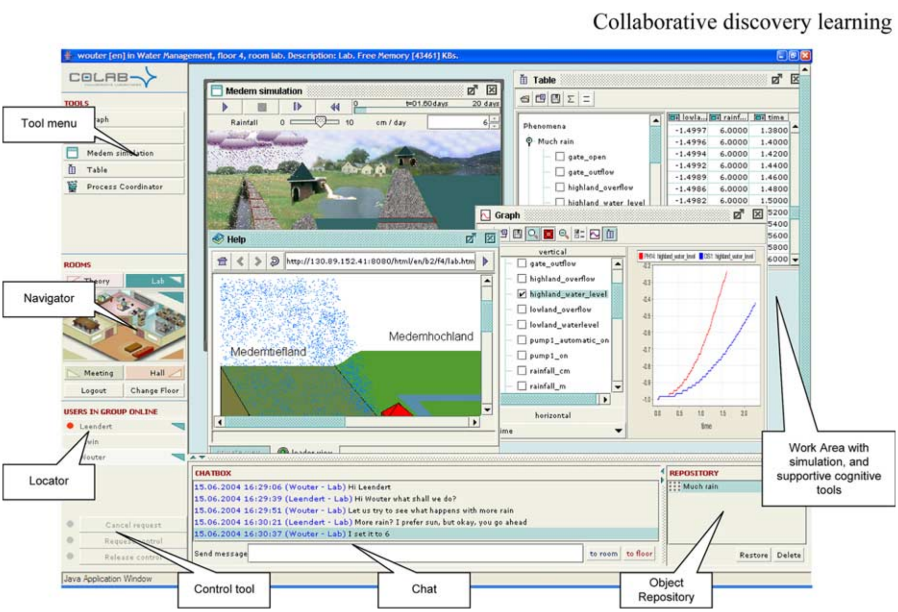

Fig. 1. Annotated screenshot of Co-Lab's interface.

3. Co-Lab's collaborative discovery learning orientation

In collaborative discovery learning, groups of students examine scientific phenomena and express their shared understanding in a runnable computer model. Learners thus engage in three analytically distinct processes, namely inquiry, modeling and collaboration. However, in Co-Lab the demarcation between these processes is less clear cut. Collaboration, for instance, runs as a continuous thread through the discovery learning process, affecting the way in which inquiry and modeling processes are performed and should be supported. Furthermore, modeling is integral to the inquiry process. Learners express their initial understanding of scientific phenomena in a model sketch, which is then used to predict and explain what will occur in the phenomena being modeled. By testing these hypotheses with the simulation or the remote lab, learners gain knowledge they can use to refine or extend their model.

The sections below detail Co-Lab's orientation to collaborative discovery learning. The processes of inquiry, modeling, and collaboration are described in separate sections, despite the dynamic interplay between them.

4. Facilitating inquiry learning

Inquiry learning pertains to the acquisition of knowledge by a learner-regulated process of data collection and data interpretation. The inferential processes that build upon the data gathered by the learner should lead to the discovery of rules that govern the relations between variables in a given domain. This means that inquiry learning has shifted from the discovery of concepts (as it was originally conceived in Gestalt psychology and the work of Bruner (1961)) to discovery of rules (De Jong & Van Joolingen, 1998).

In Co-Lab, learners can collect data from built-in simulations, remote laboratories and remote databases. Regardless of the type of data source, learners are to unravel the relations between input and output variables through systematic experimentation. This process proceeds through five phases: analysis, hypothesis generation, experiment design, data interpretation, and conclusion. Njoo and De Jong (1993) coined the term *transformative processes* to indicate that the learners' activities in these phases are performed for the sole purpose of yielding knowledge. *Regulatory processes*, in contrast, serve to manage and control the inquiry learning process. Planning, monitoring and evaluation are typical instances of regulatory processes.

A review by De Jong and Van Joolingen (1998) has produced a comprehensive overview of the difficulties learners encounter in inquiry learning. How these problems were addressed in Co-Lab is discussed in the sections below.

4.1. Support for transformative processes

4.1.1. Hypothesis generation

One of the most pertinent problems in inquiry learning is formulating syntactically correct (i.e., testable) hypotheses. One solution is to provide learners with partly specified hypotheses. Van Joolingen and De Jong (1993) introduced a hypothesis scratchpad which contained templates to formulate syntactically correct predictions. Learners could select a statement from a pull-down menu and complete it by adding variables, relations and condition. Unfortunately, usability problems prevented learners from taking full advantage of this tool.

Bearing these problems in mind, Gijlers and De Jong (2004) converted the ideas of the hypotheses scratchpad into a proposition table. This tool comprised a list of fully specified hypotheses, the students' beliefs about a hypothesis and their willingness to test it (the proposition table was used in a collaborative setting). Students using the proposition table outperformed both the hypotheses scratchpad and the control group on a test measuring intuitive knowledge. Protocol analysis revealed that these differences arose because students in the proposition table group produced more statements about hypothesis generation and discussed a larger number of hypotheses.

Despite these favorable results, offering fully specified hypotheses has the potential disadvantage of revealing the key variables and relations to the learner. This might cause learners to skip the analysis phase and start experimenting on the basis of patchy knowledge. Co-Lab supports hypothesis construction in a graphical instead of a verbal way, using the built-in modeling tool in order to restrain learners from jumping the gun. Learners use their model to express their propositions about a relation between two variables. During the initial stages, pre-specified, qualitative relations can be selected from a drop-down menu. Hypotheses can be tested by comparing the outcomes of the model with the simulation's output. During the later stages, qualitative relations can gradually be replaced by quantitative ones, using scientific formulas.

4.1.2. Experiment design

Another class of problems pertains to the design of experiments. These include the design of inconclusive experiments, inefficient experimentation behavior, and the design of experiments that are not intended to test a hypothesis.

Inconclusive experiments often arise because learners vary too many variables at once. Experimentation hints such as "vary only one variable at a time" can improve learners' experimentation behavior in this respect (De Jong & Van Joolingen, 1998). In Co-Lab, such hints are offered in the Process Coordinator and in help files.

Inefficient experimentation occurs when learners fail to design informative experiments or when they repeat previous experiments. The former may be difficult to overcome because inquiry learning essentially is a learner-directed process. Repetitions on the other hand might be avoided by providing insight into the experiments a learner has already performed. To this end, SimQuest (Van Joolingen & De Jong, 2003) simulations contain a monitoring tool that shows the initial values of input variables and end values of output variables for each experiment (Veermans, 2002). Learners can reveal the progress of output variables across time by selecting a given experiment from the tool and clicking the 'replay' button. The simulation is then run using the exact same settings as in the original experiment.

Experimentation support in Co-Lab is more output-oriented in that learners can save experimental results instead of experimental settings. Learners can save tables and graphs in the Object Repository and annotate these to identify the settings used in the experiment. Tables and graphs can be retrieved by clicking the 'restore' button (see Fig. 1).

Designing experiments that are *not intended to test hypotheses* can be indicative of an *engineering approach*. Schauble, Klopfer, and Raghavan (1991) characterize this approach as one in which learners attempt to create a desirable outcome instead of trying to understand the model. Co-Lab seeks to resolve this problem by requiring learners to produce a comprehensive model. Assignments in Co-Lab are therefore open-ended, merely instructing learners to come to grips with a phenomenon and model it. However, research suggests that additional experimentation hints are needed. An exploratory study with Co-Lab revealed that experimentation in absence of any further support to the contrary shows learners engaging in an engineering approach (Manlove & Lazonder, 2004). Learners merely used the water tank simulation (displayed in Fig. 1) to reach equilibrium through trial-and-error. Once they succeeded, they did not try to discover the simulation's underlying model by reaching equilibrium using different settings (as suggested in the text of the assignment).

4.2. Data interpretation

Learners often experience difficulties in drawing conclusions from their data. Visualizing data is a well-tried solution. A linear relationship between two variables can, for instance, more easily be identified from a graph than from numerical values in a table. Nevertheless the construction and interpretation of graphs appears to be both time consuming and error prone. Co-Lab's graph tool therefore automatically generates a graph when the simulation is run. Learners can thus readily interpret the results without having to convert raw data into a graph.

Co-Lab does support across-experiment comparison of data by allowing the learner to compare the plots of the results of more than one experiment in one graph. An interesting extension could be to add the extended version of Veermans' (2002) monitoring tool to the Co-Lab environment which allows learners to arrange stored experiments according to one of the variables to compare various experiments. Between experiment comparison is further supported by a graphing option that allows learners to plot the end value of an output variable obtained in a series of experiments in a single graph. This option supports learners in performing a meta-analysis of their own data to extrapolate relations between variables.

4.3. Support for regulatory processes

Regulatory processes are pivotal to successful inquiry learning. While constructivists advocate that learners should independently engage regulatory activities such as planning, monitoring and evaluation, research has consistently shown that additional support is needed for learners to become "active agents of their own inquiry learning" (Kluwe, 1982).

Task complexity can get in the way of learners' spontaneous use of self-regulatory skills (Elshout, 1987). This problem might be overcome by scaffolding the inquiry process along a spectrum of progression. This so-called model progression allows learners to start with a simplified version of the simulation; complexity is gradually increased by introducing new variables or features during the course of the learning process (De Jong & Van Joolingen, 1998). In Co-Lab, the floors within a building represent the various levels of complexity. To illustrate, model progression in the water management building develops from a simulation of a water tank, through a real water tank (accessible via a remote lab), to an advanced simulation of polders and rivers that includes tidal movement, rainfall, and pumping stations.

While model progression enables learners to employ existing self-regulatory skills, it does not cater for the use of unmastered skills. To provide the latter type of support, specific features or tools are implemented in the learning environment. The sections below discuss measures for promoting planning, monitoring and evaluation.

4.4. Planning

Planning is supported in Co-Lab by outlining the steps learners should take during each phase of the inquiry process. This type of suppsort is particularly useful for learners with lower levels of self-regulation (Vermunt, 1998), and research suggests that Co-Lab's target audience matches this profile. Manlove and Lazonder (2004) report that Co-Lab users between the ages of 15 and 17 hardly engaged in planning and frequently expressed their ignorance of the general approach to the learning task. This observation prompted the development of a fully specified planning tool called the Process Coordinator (see Fig. 2). It contains a series of goals and subgoals that guide learners through the stages of the inquiry process. Each goal statement comes with a description stating what learners should do to accomplish that goal, and one or more hints that answer frequently asked questions. The purpose of this design is to promote self-regulation which in turn will yield higher knowledge gains. Attempts to validate this assumption are in progress.

As learners' self-regulatory skills are expected to improve, planning support can be gradually faded. In keeping with the building metaphor, the Process Coordinator contains fewer and less explicit directions on higher floors. Fading may occur by removing the subgoals, the descriptions, and the hints in any preferred order. Finally, also the top level goals can be removed, leaving an open, unspecified planning tool. The Process Coordinator thus provides a temporary support structure which can be considered another instance of model progression.

4.4.1. Monitoring

In the monitoring phase, learners engage in control and observation of both their comprehension, attention, and performance in relation to the goals set during the analysis phase. Monitoring can be triggered internally (e.g., learners spontaneously consider their approach to the inquiry task) and externally (e.g., inconsistent results

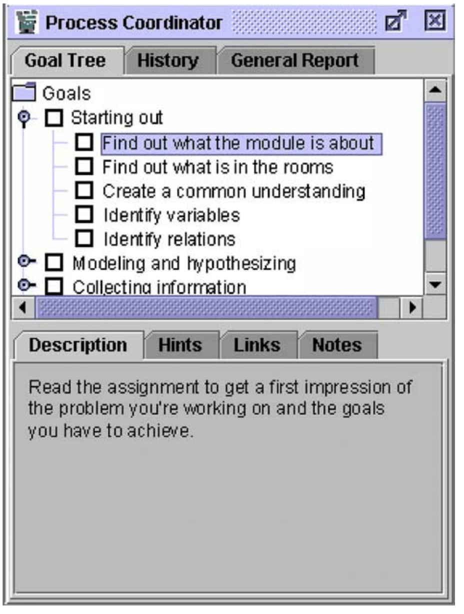

Fig. 2. Screenshot of the Process Coordinator.

prompt learners to check the simulation's settings). It is therefore somewhat difficult to anticipate exactly when monitoring will (or should) occur. This in turn complicates the design of specific monitoring support – at least, without an intelligent tutoring system (cf. Veermans, 2002).

Monitoring is supported by giving overviews of the learner's actions in the environment (De Jong & Van Joolingen, 1998). While Co-Lab does not provide ready-made overviews, it does facilitate learners in compiling overviews themselves. In the Process Coordinator, learners can make notes associated to the goals present, and review these on a History page. Learners also can tick off goals they consider completed.

4.4.2. Evaluation

Evaluation pertains to a judgment of learning outcome as well as the learning process. While there often is no clear-cut distinction between evaluation and monitoring, Schön (1991) differentiates between reflection on action from reflection in action. Reflection in action pertains to monitoring activities, whereas reflection on action can be likened to evaluation activities which occur at "certain stopping points" during an activity, often at the end of the learning process.

Process displays and process prompts have been used to promote evaluation of learners engaged in discovery learning (Lin, Hmelo, Kinzer, & Secules, 1999). A process display shows explicitly to learners what they are doing to solve a task. In learning environments this is often a trace or history of student actions. Process prompts give learners the opportunity "...to explain and evaluate what they do before during and after problem solving acts'' (Lin et al., 1999). These prompts are usually in the form of questions posed to the student by the learning environment. Lin and Lehman's (1999) study of different prompt types found that prompting learners to justify their reasoning directed learner's attention more to understanding ''when, why, and how to employ experiment design principles and strategies'' (p. 837). This in turn enabled better transfer of their understanding to novel problems.

Co-Lab utilizes both process displays and process prompts via the multiple views within the Process Coordinator. In the goal view, a process model is supplied to the learners in the form of goals and subgoals which gives learners an overview of the process they should engage in. The process prompts are supplied in the form of hints per sub-goal and take a question and answer format. The history view within the process coordinator shows all learner actions organized under the goals provided. Finally both the history and the goal views are combined within the report view. It enables learners to see their goal progress within the goal view, along with the notes and products they have made in the history view. The report view also provides a template structure where learners write a report of their findings. The template specifies report sections along with descriptions which assist learners in writing out what they have learned from their inquiries and what they have learned about the process of inquiry.

5. Facilitating modeling

Mental models are the internal representations we hold of our world. We use them to provide insight into how to reason over a particular problem, domain or situation (Jonassen, 1995). Assisting learners in acquiring appropriate mental models of physical systems is one of the main purposes of scientific discovery learning. Computer modeling has been recognized as an effective method to facilitate mental model development. By building an executable domain model, learners externalize and test their conceptions of the variables in the simulation. The role of the model thus is to house domain knowledge and to be a vehicle for students' understanding and conceptual change (Jonassen, Strobel, & Gottdenker, in press).

There are many types of modeling formalisms, from concept map notations to text based modeling found, for example, in goal tree structures (e.g., Löhner, Van Joolingen, & Savelsbergh, 2003). When reasoning about the continuous physical systems found in water management and green house gasses however, systems dynamics modeling appears to be the most appropriate to represent these systems (Frederiksen & White, 1998; Jackson, Stratford, Krajcik, & Soloway, 1996). Such models reflect the dynamic nature of physical systems, by allowing simulation, envisioning the consequences of all direct and indirect relationships between variables in a time-dependent system. The use of generic variable types such as stocks, constants and auxiliaries provide learners with ''mini'' mental models of how to think about variables and their relationships in the system. The Co-Lab environment contains a Model Editor tool which allows learners to construct systems dynamic models of the phenomena displayed in the simulation.

When learners construct a model, they tend to go through four stages: (1) model sketching, (2) model specification, (3) data interpretation, and (4) model revision (cf. Hogan & Thomas, 2001). As Co-Lab perceives modeling as an integral part of scientific inquiry, the stages in the modeling process are closely related to the phases of the inquiry learning process identified by Njoo and De Jong (1993). In the orientation phase, learners sketch a model outline to express their initial understanding of the phenomena from the simulation. In the hypothesis phase, this sketch is transformed into a runnable model by specifying the relations between the variables in the model. During data interpretation, learners compare their model to data from the simulation which, during the conclusion phase, feeds their decision to revise the model.

Given the intertwined nature of inquiry and modeling, much of the support which has been explained in the previous sections also applies to supporting modeling activities. The sections below therefore present the support learners can use for model building per se.

5.1. Support for model sketching

During problem analysis, learners can make a situation drawing to express their initial mental model and understanding of a domain (Forbus, Carney, Harris, & Sherin, 2001; Oliver & Hannafin, 2001). The sketch often serves to scaffold the complexities found in simulation-based inquiry learning, where learners have to unravel various, simultaneously interacting cause/effect relationships (Jackson et al., 1996). Co-Lab supports model sketching through a graphical modeling tool which allows learners to build an icon-based model structure (see Fig. 3). Additionally, learners are supported within Co-Lab in learning systems dynamic modeling via a tutorial and model editor help files.

5.1.1. Support for model specification

In model specification, learners define the relations between variables in their model. These relations initially represent a learner's assumptions of how variables interact; later the relations represent the learner's insights derived from the simulation. According to Löhner et al. (2003), qualitative specifications are appropriate during the initial stages of the modeling process when learners still lack a clear understanding of the model they are building. In fact scientists in practice often start with a qualitatively expressed model (White & Frederiksen, 1990). By qualitatively expressing relationships, learners begin to construct a bridge between their initial mental model of the system (as found in the model sketch) and the target model (Jackson et al., 1996). Quantitative, formula-based specifications are more useful for the later part of the modeling process, when the model is finalized. As both forms of representation play a distinct role in the modeling process, learners are best supported by a modeling tool that accommodates a mixed representation.

Co-Lab's Model Editor was designed according to these guidelines. It allows learners to specify their model by selecting pre-defined qualitative relations, drawing

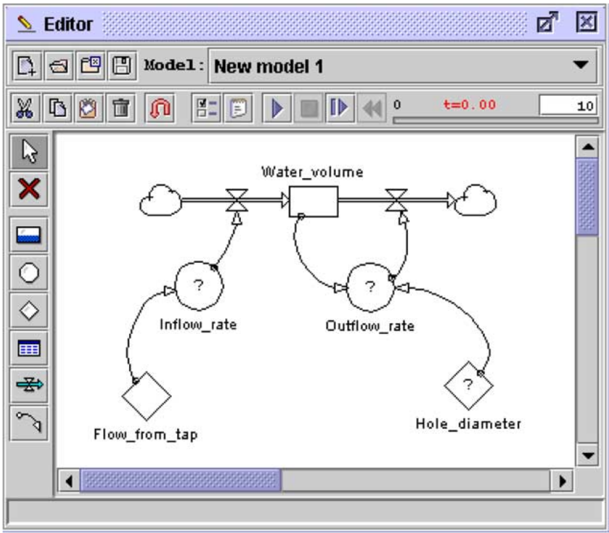

Fig. 3. Screenshot of the Model Editor.

graphs, or entering mathematical formulas (see Fig. 4). As variable and property identification progresses across a qualitative to quantitative spectrum (Njoo & De Jong, 1993), learners are prompted to specify their model accordingly, using qualitative relations to specify their hypotheses and quantitative relations to express insights derived from the simulation.

5.2. Support for data interpretation and model revision

Running a model to generate data is the primary means of model testing and revising (Forbus et al., 2001; Frederiksen & White, 1998). The data resulting from model runs need to be interpreted by the learner to establish how well the data from their model match with the results from the simulation. This intrinsic feedback a model can give is an important factor also in assisting students in evaluating their domain understanding (Jackson et al., 1996).

To facilitate the comparison of data between simulation runs and model runs, Co-Lab facilitates the display of the output of the experiments with the simulation or remote lab and the learner-constructed model in a single graph (see Fig. 1). Additionally a curve fitting tool can help the learners in constructing a model by performing a statistical analysis on the data collected. When learners select this option, the system calculates the goodness of fit between the model output (as shown in the graph) and a given theoretical distribution (e.g., a curvilinear relationship).

Examining and interpreting model output is essential for understanding scientific phenomena. Yet research shows that students use model output sparingly, usually only at the end of a modeling session to check if obtained results match their initial expectations (Hogan & Thomas, 2001; Stratford, Krajcik, & Soloway, 1997). Modeling should

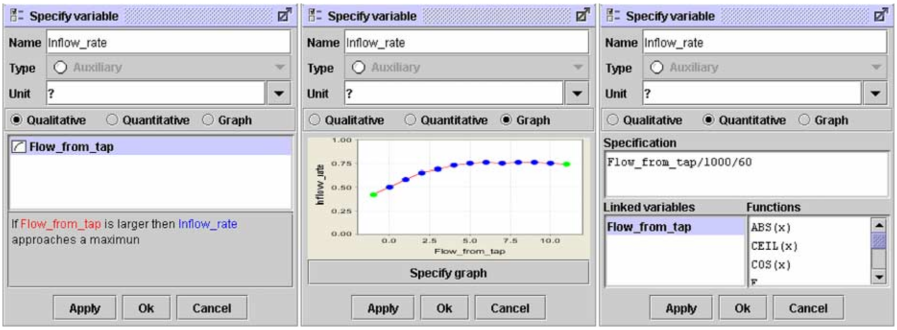

Fig. 4. Qualitative, graphical, and quantitative specification of relations in a model.

involve dynamic iterations between examining output and revising models. As learners generally fail to spontaneously adopt such an iterative approach, the learning environment should prompt them to do so. In Co-Lab, these prompts are offered in the Process Coordinator, fully integrated with the directions for systematic experimentation.

6. Facilitating collaboration

In order for students to "act like scientists", a discovery learning environment should support working in collaborative groups. An additional advantage of collaboration is that it promotes higher achievement than individual learning strategies (e.g., Lou et al., 1996). Other studies have shown that this effect transfers to discovery learning. Paired students generally are more successful in discovering scientific mechanisms than single students (e.g., Okada & Simon, 1997; Teasley, 1995). These studies further demonstrate that the superiority of student pairs is attributable to peer interaction. Collaboration increases the likelihood that learners engage in the type of talk that supports learning, such as asking and answering of questions, reasoning and conflict resolution.

Collaboration also promotes regulation of the learning task. In a study by Lazonder (submitted), pairs of students showed relatively higher proportions of self-regulatory activities than single students. More specifically, dyads exhibited a richer repertoire of strategies to solve problems. They were also more proficient in monitoring each other's actions which facilitated early detection and correction of errors. The results for evaluation also differed in favor of the dyads. They crosschecked initial answers more frequently and modified initially incorrect responses more than twice as often. Further research is needed to determine if these effects generalize to discovery learning.

These studies however, focused on face-to-face collaboration. Comparisons of computer-mediated and face-to-face collaboration suggest that computer-mediated collaboration is characterized by a number of deficiencies. A number of studies have, for instance, found that face-to-face dyads attain higher performance scores than students who collaborate online (e.g., Salminen, Marttunen, & Laurinen, 2003; Van der Meijden & Veenman, in press). Face-to-face dyads also have more prolonged discussions on the learning task; communication in the computer-mediated dyads is more directed at coordinating efforts, operating the communication tool, and expressing emotions.

Together, these findings indicate that computer-mediated collaboration can promote scientific discovery learning, but that collaboration itself should be promoted for learners to take full advantage of each others presence. This implication is relevant to Co-Lab, as this environment is designed for synchronous online collaboration, permitting learners to work together in real time while being geographically dispersed.

Co-Lab allows for this type of collaboration by providing several means of support for collaboration. The Co-Lab environment is a shared space, in which learners can see each others actions and to which each learner can contribute. Also Co-Lab includes a communication channel based on chat, as well as a place for storing commonly built objects as well as and functions that increase social presence. These kinds of support for collaboration are elaborated below.

Although such supportive features are available (e.g., reflective notebooks, collaborative concept maps, communication widgets), their efficacy in synchronous online collaboration has not yet been assessed. Yet empirical validation is needed because Co-Lab's target audience is familiar with online communication technologies. To illustrate, Lazonder, Wilhelm, and Ootes (2003) examined the efficacy of sentence openers to foster peer interaction. Sentence openers are pre-defined opening phrases students can readily select from a menu in their chat tool. The students in this study hardly used sentence openers, a result that was attributable to their chat experience. Students were accustomed to typing chat messages and maintained in this chat style, being unwilling or unable to adopt an alternative way to create messages. This lead to the decision that sentence openers should not be included in Co-Lab.

6.1. Support for student interaction

Peer-to-peer collaboration encourages students to articulate their thoughts, which in turn has a facilitative effect on achievement and regulation. Co-Lab enables social interaction through a chat tool. Consistent with the building metaphor, the chat is room-specific, which means that by default messages can only be read in the room in which they were sent.

Usability tests revealed that this division was too strict as it impeded the learning discourse. Learners specifically asked for an "intercom" to contact group members in different rooms. This functionality was implemented in the form of the "Send to floor" button. By pressing this button, the unsent chat message becomes visible in every room.

6.2. Support for shared knowledge building

Constructing shared knowledge is the ultimate goal of collaborative learning. This goal has two important consequences for the tools in collaborative discovery learning environments. One is that shared knowledge must be represented explicitly so learners can see the objects they are working on and talking about. Learners should thus be offered a joint space to post their ideas, hypotheses, models and so on. The second implication is that the learners' multiple perspectives should be integrated. This means that the tools should allow learners to manipulate the objects represented in the joint space.

The notion of shared workspaces was central to the design of Co-Lab. In a way, Co-Lab itself is one shared workspace: the environment holds no private tools or spaces, so everything a learner does is readily visible to and editable by his/her group members. To ensure that the collaboration proceeds in an orderly way, Co-Lab introduces the notion of *control*. In each room only one learner (the "leader") can perform all actions; the others are merely allowed to do reversible actions that have no permanent trace in the learning environment. What is considered to be reversible action can be controlled on a tool-by-tool and even a button-by-button basis. An example of a reversible action is choosing a plot of a specific variable out of an existing data set, i.e. opening a specific view on existing data. An irreversible action would be creating a new data set, or making changes to a model. Learners can request and pass on control to each other by means of a dedicated control tool, which uses a traffic light metaphor.

6.3. Support for social presence

Face-to-face collaboration is dominated by social presence (a sense of being together) where individuals can interact effortlessly. As online collaboration is weak in social presence, designated tools are needed to increase learner's sense of being together (Kirschner, 2002). Co-Lab's Locator tool allows learners to check which group members are online and which room they are in. Manlove and Lazonder (2004) showed that learners use this tool frequently to see if group members have entered the environment or joined them when changing rooms. The Locator also served to trace group members who did not contribute to the ongoing chat discussion.

7. Co-Lab evaluation studies

Apart from initial specification studies and usability studies mentioned above, that lead to modifications of Co-Lab design, Co-Lab has been evaluated with learners in two formative and two summative evaluation studies. The results of the formative evaluation studies also contributed to the final product. The current section will briefly describe these studies. Full reports are available in Lazonder (2004). As Co-Lab is a large comprehensive system, evaluation studies have had to focus on specific aspects of it, rather than evaluating the whole system.

The first formative evaluation study focused on learners' general impressions of the system. The goal was to evaluate whether students are able to use the Co-Lab environment in its natural state. To this end learners ($N = 43$) went through a full Co-Lab session, although the model in this session was relatively simple. Learners' actions were logged and they filled in a questionnaire after completing the session. This lead to a number of remarks regarding the room metaphor and workflow within the environment: in a complex environment like Co-Lab students indicate a high need for transparency (knowing what is the current task, knowing where co-workers are, knowing where information can be found) as well as a need to improve the means for collaborative tasks, such as planning and encouraging. This lead to changes in communication (chat across rooms) and to the availability of the process coordinator in every room.

The second formative evaluation study examined efficiency in terms of how students work with Co-Lab with minimal guidance from evaluators or the environment. The goal was to (1) describe working patterns and group approaches to the learning task and to obtain base-line data which shows how students are or are not regulating their inquiry. Students ($N = 39$) worked in a minimally guided Co-Lab environment on a simple inquiry task. It was found that in the early stages of the session, the lab work prevailed; learners showed a preference for the lab room, only later on modeling and more systematic experimentation were taken on by the learners. With respect to regulation it was found that most regulation effort went toward regulating the collaborative process, rather than the learning task. Again this supports the suggestion to integrate tools designed to promote learners' regulation into rooms where the inquiry task is being performed.

In the first summative evaluation study, the collaboration as envisioned by Co-Lab was compared to a face-to-face collaboration setting. The purpose was to investigate in what way the on-line communication mode in Co-Lab would influence the task attainment in Co-Lab, compared to the more traditional face-to-face mode. Students ($N = 40$) worked on two Co-Lab floors, where the first served an introductory purpose. The analysis focused mainly on the modeling task. It was found that there was no significant difference in product of learning (the quality of the created models), but there were differences in process. Face-to-face working students showed more superficial behavior and actions of specifying model values had a negative effect on learning product, which was not the case for the on-line collaborating dyads. This indicates that the two collaborative modes are essentially different, and that the on-line collaborative mode employed by Co-Lab can promote deeper processing.

Finally, the second summative study specifically evaluated the process coordinator that is present in Co-Lab. The study compared two groups of students ($N = 61$), one working with a pre-filled process coordinator, and one for which this tool was left empty, and for which students had to fill it themselves. The group with the filled process coordinator performed more planning actions and used the process coordinator more often than the other group. This study supports research indicating the students need scaffolds such as the process coordinator in order to fully benefit from the complexity and richness of the data provided for them, when working in environments like Co-Lab.

8. Conclusion

In this contribution, the Co-Lab learning environment served as a vehicle to express the authors' views on collaborative discovery learning. Co-Lab's initial design was based on insights gleaned from instructional theory and empirical research. Usability tests were conducted to improve the user-friendliness of the environment and the intuitiveness of its tools. Formative and summative evaluations were also performed to assess Co-Labs potential to foster collaborative inquiry learning.

As an environment, Co-Lab is suitable to provide a means for an integrated approach for collaboration, modeling and inquiry. Co-Lab is the first environment in which these three learning modes are brought together and integrated. Co-Lab's structure keeps the complexity of the environment within reasonable limits, as may be inferred from the unguided activities that learners have undertaken. Also specific instructional support, such as the process coordinator, qualitative modeling and the offering of challenging assignments provides a means for engaging students in an authentic inquiry context.

The studies performed with Co-Lab indicate that the way of offering support is well on track, however more research is needed to understand Co-Lab and to make sure that Co-Lab will eventually be used in classrooms. Research is needed and planned into the assessment of learning in collaborative inquiry environments: how can we assess learning products such as inquiry skills, deeper domain knowledge and skills for collaboration. Although attempts have been made to measure knowledge from discovery learning (Swaak & De Jong, 1996) more research is needed to cover the full range of knowledge types that express a learner's proficiency in inquiry and modeling.

In order to bring Co-Lab to actual education more research and development is also needed. As such Co-Lab represents a developmental end point towards collaborative inquiry, but a path leading to this end point has not yet been laid out. Teachers will not accept the use of an integrated system like Co-Lab immediately, thus an implementation trajectory needs to be carefully designed. A follow-up project, called ReCoIL (Resoirces for Collaborative Inquiry Learning) is currently underway in providing such an implementation strategy.

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