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FACILITATING LEARNING FROM COMPUTER-SUPPORTED COLLABORATIVE INQUIRY: THE CHALLENGE OF DIRECTING LEARNERS' INTERACTIONS TO USEFUL ENDS

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Chemistry problems can be tough nuts to crack for students, particularly when the problems are of a mathematical type. Collaborative inquiry activities that are embedded in computer-supported learning environments can provide students with opportunities to construct the kind of knowledge required to solve complex chemistry problems. Yet, directing learners' collaborative inquiry in computer-supported learning environments to such useful ends remains a challenge. In this article, we introduce a new approach to facilitating learning from computer-supported collaborative inquiry. The approach we present is a collaboration script that guides pairs of learners through a sequence of inquiry activities and prompts effective interactions in an adaptive fashion. We developed an initial version of a learning environment that included the collaboration script, a simulated chemistry laboratory and a note-taking and mind-mapping tool. In an experimental study involving two conditions (scripted collaboration, unscripted collaboration), we had pairs of students work on a stoichiometry problem using the learning environment. We compared the learning outcomes and learning experiences of the two conditions, and explored learner-learner and learner-system interactions employing a case study methodology. Based on the quantitative and qualitative results, we derived a set of design recommendations for the next development cycle. Our main recommendations are to (a) inform learners about the value of the script support, (b) add algebra practice items and some general chemistry instruction to the learning environment as well as support for interrelating the multiple external representations in the simulated chemistry laboratory, (c) develop tools for assessing learners' prior knowledge and skills in collaborative inquiry learning, general chemistry and basic algebra, (d) increase the degree to which the learning environment can adapt to different learner needs, and (e) improve the interface and interaction design of the simulated chemistry laboratory.

Keywords: Collaborative inquiry learning; computer support; scripting.

1. Introduction

How much hydrogen and how much nitrogen are needed to produce two tons of ammonia? What is the maximum mass of iron that can be obtained from two tons of iron ore? When asked to solve chemistry problems, more precisely, stoichiometry problems, similar to these (let alone more complex ones) high school and college students across the world have considerable difficulty (e.g. BouJaoude & Barakat, 2000; Gabel *et al.*, 1984; Schmidt, 1990, 1992). Yet, the ability to solve stoichiometry problems is of high relevance in chemistry research and practice, including many medical fields and branches of the industry. Researchers found that deficiencies in conceptual knowledge, that is, knowledge of the theories, principles and chemical processes underlying the problems, account for most of the difficulties students have in solving stoichiometry problems (e.g. BouJaoude & Barakat, 2003; Schmidt, 1990, 1992). This finding gives rise to the question of what can be done to help students acquire deeper understanding of stoichiometric concepts.

Empirical evidence indicates that inquiry learning can promote the acquisition of conceptual knowledge. Numerous computer-based learning environments have been developed to enable and support students' inquiry activities, for example, the *Web-based science inquiry environment* (WISE, http://wise.berkeley.edu/) or *SimQuest* (http://www.simquest.nl/learn.htm). Yet, simulations and cognitive tools appear to be insufficient to secure the benefits of inquiry learning (e.g. de Jong & van Joolingen, 1998). Therefore, the design of several such environments (e.g. *Co-Lab*, http://www.co-lab.nl/) was extended to include collaborative learning, another instructional approach that can help learners to acquire deep understanding of the theories, concepts and principles underlying complex problems. *CoChemEx* (Tsovaltzi *et al.*, 2008) constitutes an example of a computer-based learning environment that enables collaborative inquiry learning. Against the background of research on unsupported collaborative inquiry learning, a collaboration script was implemented in CoChemEx. The script constitutes a novel approach to facilitating collaborative inquiry in that it combines structural and adaptive support. The implementation of the script represented the first step of a design cycle geared towards support for collaborative inquiry learning that automatically adapts to learner needs. On-going design efforts have focussed on the conceptual development of the collaboration script and on the development of automated assessment facilities within CoChemEx.

In this article, we describe the conceptual development of the collaboration script and report a full test run of a learning environment that included the collaboration script. While building on knowledge gained through our involvement in the development of CoChemEx and using some of the same components as CoChemEx, the present learning environment constitutes a prototype as it has been developed specifically for use with high school students in Germany. In the initial exploratory study we report in this paper, we had pairs of students work on a stoichiometry problem using the learning environment and analyzed their learning outcomes, collaboration and inquiry, interactions with the system and learning experiences.

Following the principles of design-oriented research (e.g. Brown, 1992; Cobb *et al.*, 2003; Schoenfeld, 2006), we derived a set of design recommendations from the test run that will feed into another cycle of development and testing. These design recommendations are presented at the end of this paper.

2. Background

In the following, we provide a review of the theoretical and empirical background that informed the design of the stoichiometry learning environment and shaped our research. It needs to be pointed out that our design efforts and research program are situated in a European tradition of research on inquiry learning, which manifests itself in projects such as Co-Lab (van Joolingen *et al.*, 2005). In this tradition, inquiry activities (generating a hypothesis, manipulating variables, interpreting results, etc.) are set apart and often arranged in sequence either through explicit instruction or through system affordances. Structuring students' inquiry in such a way is regarded necessary against the background of learners' science process skills and limited prior knowledge in the domain under study. Although the notion of open-ended, project-based inquiry has replaced this understanding of inquiry learning in a large part of the learning sciences community many studies following up on research in the former tradition continue to be conducted in Europe. Hence, the following review focuses on a particular strand of research on inquiry learning. The reader is referred to the works of other authors, particularly those of John D. Bransford, Marcia C. Linn, Brian J. Reiser, James D. Slotta, Nancy B. Songer, Daniel D. Suthers, Robert F. Tinker and Barbara Y. White for a broader perspective on technology-enhanced inquiry learning in science.

2.1. *Experimentation in chemistry education: The benefits and challenges of inquiry learning*

Experimentation plays a major role in chemistry education, taking various shapes depending on the pedagogical philosophies drawn on by teachers and instructional designers. The more traditional approaches call for experiments to be planned and performed by the teacher. Other approaches encourage student laboratory work, the implementation of which ranges from reproductive experimentation, which limits the students' task to carrying out a specified procedure and verifying a given chemical reaction, to free experimentation, which leaves it up to the students what experiments to design and conduct in order to solve a given task. Free experimentation can be regarded as an instance of (scientific) inquiry or discovery learning, a pedagogical philosophy that emphasizes the active role of the learners in instructional contexts. In inquiry learning environments, the learners do not receive direct instruction on the target concepts. Instead, they are encouraged to construct knowledge from the experiences and examples they obtain through experimentation or modelling (de Jong & van Joolingen, 1998).

Researchers have highlighted the similarities between the learning processes that characterize inquiry learning in scientific disciplines and the activities and cognitive processes leading to scientific discovery: "In scientific discovery learning learners more or less take the role of scientists who want to design theory based on empirical observations" (de Jong, 2005, p. 215). Because of the parallels between inquiry learning and scientific discovery the former is typically modeled on the latter. A well-known model of inquiry learning in scientific disciplines, which draws on models of scientific discovery, is that by de Jong and his colleagues. They refined their model through more than a decade and a half of research. In a recent article, de Jong (2006) distinguished five learning processes that make up what he termed the *inquiry cycle*: During (1) *orientation*, the learner coarsely analyzes the problem that is to be solved. This is followed by the processes of (2) *hypothesis generation* and (3) *experimentation* with the latter comprising the subprocesses of experiment design, prediction and data interpretation. The remaining two learning processes are (4) *conclusion* and (5) *evaluation*. During conclusion, the learner decides on the validity of the hypothesis tested by means of experimentation. During evaluation, the learner engages in "a reflection on the learning process and the domain knowledge acquired" (p. 109). de Jong emphasized that the learning processes may occur in an iterative fashion, with one process being initiated before the previous one has been completed. He also pointed out that metacognitive processes, that is, monitoring and planning, complement the inquiry cycle.

Drawing on models of inquiry learning such as that of de Jong (2006), it can be assumed that free experimentation yields learning when the learners "take the role of scientists" (de Jong, 2005, p. 215), engaging in all of the learning processes that make up the inquiry cycle. Yet, when inquiry learning is put into practice, be it in chemistry or in any other scientific discipline, this is where the challenge begins. Inquiry learning has to be supported in an appropriate manner for the learning processes to take effect because the cycle of orientation, hypothesis generation, experimentation, conclusion and evaluation rarely occurs spontaneously in inquiry learning environments (de Jong & van Joolingen, 1998). Instead, the learners often show unproductive or even counterproductive behavior during inquiry activities (such as experimentation and modelling), which ultimately leads to situations in which the potential benefits of inquiry learning do not unfold (Hmelo-Silver *et al.*, 2007). For example, learners tend to generate incomplete hypotheses, ignore conflicting evidence or seek confirming evidence only (de Jong & van Joolingen, 1998).

2.2. *Computer-based learning environments for inquiry learning in chemistry*

Technology can serve various functions in inquiry learning settings. In chemistry education, the most obvious function is that of enabling inquiry activities. Computer-based learning environments offer opportunities for students to engage in experimentation and modeling activities that could not be realized without computers. Several constraints apply to the types of real chemistry experiments that can be planned and carried out by the students themselves, including safety issues, the complexity of the setup and procedures, and the cost of chemicals, glassware and measuring equipment. Computer-based learning environments, more precisely simulations, are not affected by these constraints. Using a simulation, learners can plan and carry out an unlimited number of experiments of varying degrees of complexity on their own. The *Molecular Workbench* (http://workbench.concord.org/) can be considered an excellent example of a simulation environment that enables inquiry learning in chemistry. Students can use the Molecular Workbench to experiment with various chemical reagents, observe reactions at the microscopic level, test hypotheses and explore relationships among reagents and products. Neither could these experiments be carried out nor would observations at the microscopic level be feasible in a student laboratory (The Concord Consortium, n.d.).

As pointed out in the preceding section, inquiry learning has to be supported for its potential benefits to unfold. De Jong and his colleagues have proposed to provide instructional support for inquiry learning through cognitive scaffolds (e.g. de Jong, 2006). The majority of cognitive scaffolds to be found in the research literature on inquiry learning take the form of tools that are integrated into computer-based learning environments, an example of which is *Co-Lab* (van Joolingen *et al.*, 2005).

Furthermore, technology can be employed to create new opportunities for learning from inquiry. Consider the following example, which extends the framework of “barriers, biases and opportunities” (Bromme *et al.*, 2005) to inquiry learning in chemistry: A simulation of a chemistry laboratory has the advantages of reducing the time, effort and materials required to carry out experiments as well as the hazards involved in them. The downsides are the lack of faithfulness to the real experimental setup and procedures, which may be a barrier to learning, and the absence of visual and auditory sensations, which may augment certain biases in information gathering and processing. But the fact that chemical reactions occurring in a simulated laboratory are typically not realistic with regard to some aspects can be utilized to shift the learners’ attention from laboratory techniques to chemical concepts (Nakhleh *et al.*, 2002). In the same vein, the absence of visual and auditory sensations can be turned into a new opportunity for learning by shifting the focus from surface features of the experiments (fulmination, vapor, color changes) to the underlying chemical processes. Thus, computer-based learning environments can help to promote the acquisition of conceptual knowledge by enhancing inquiry learning: When they are designed accordingly they help learners to focus their knowledge construction activities on the theories, principles and chemical processes underlying the chemistry problems they are trying to solve.

An example of a computer-based learning environment for inquiry learning in chemistry that enables and supports inquiry learning is *CoChemEx* (Tsovaltzi *et al.*, 2008). CoChemEx is a learning environment that aims at facilitating conceptual chemistry learning through structured collaborative inquiry activities and adaptive

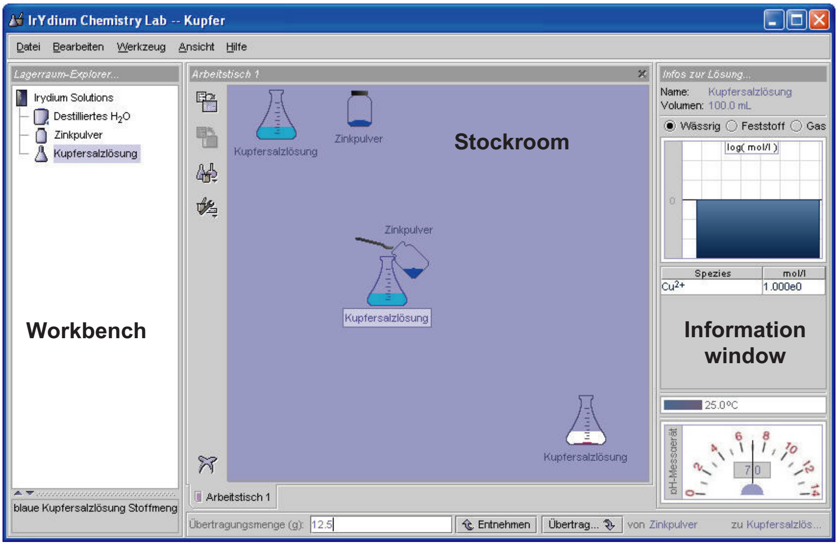

Figure 1. Annotated screenshot of the interface of the simulated chemistry laboratory *VLab* (http://www.chemcollective.org/applets/vlab.php).

scaffolds. The central component of CoChemEx is the simulated chemistry laboratory *VLab* (http://www.chemcollective.org/applets/vlab.php), an educational software environment designed to facilitate learning in various branches of chemistry, including stoichiometry (Evans *et al.*, 2008). VLab simulates a physical chemistry laboratory and has three main components (Figure 1): Experiments are conducted on the workbench where a number of tools are available to the learners. The stockroom is located to the left of the workbench. It holds an unlimited supply of the chemical reagents needed to solve a given task and distilled water. The information window is located to the right of the workbench. It displays various types of data regarding the contents of the selected piece of glassware, including volume, state of matter, molarity and temperature. VLab is the simulated chemistry laboratory that we started from when we designed our stoichiometry learning environment.

2.3. *Collaborative inquiry learning*

Before the turn of the last century, studies on inquiry learning focused almost exclusively on individual learning. Those researchers who recently turned their attention to collaborative inquiry learning (e.g. Chang *et al.*, 2003; Okada & Simon, 1997; van Joolingen *et al.*, 2005) mostly investigated the effectiveness of a computer-based learning environment or the effectiveness of some kind of cognitive scaffold that had been added to the environment. Their claim was that collaboration, that is, two or more learners solving a problem or studying a text together, enhances the effectiveness of inquiry learning with simulations and cognitive tools.

There is a general lack of empirical studies on the effects of collaborative learning in stoichiometry and in every other branch of chemistry. We were able to identify few studies that investigated collaborative learning in chemistry (Basili & Sanford, 1991; Chiu & Linn, 2008; Fasching & Erickson, 1985; Kaartinen & Kumpulainen, 2002; Tingle & Good, 1990; Towns & Grant, 1997). The studies by Chiu and Linn (2008) and Kaartinen and Kumpulainen (2002) were the only ones we were able to identify that dealt with collaborative *inquiry* learning in chemistry. Chiu and Linn (2008) had high school students study a unit on chemical reactions collaboratively using the Web-based Inquiry Science Environment (WISE). They found that the students gained a more adequate understanding of chemical reactions at all three levels of representation (macroscopic, microscopic and symbolic) from engaging in collaborative inquiry. The study also suggested that explanation prompts facilitate metacognitive monitoring and encourage subsequent metacognitive regulation with students learning collaboratively using a simulation environment. Kaartinen and Kumpulainen (2002) had 18 university students work in small groups on a learning task requiring them to engage in collaborative experimentation. Instructional support for collaboration and experimentation was not provided. Kaartinen and Kumpulainen found that the number of explicatory answers given by the students in response to a set of questions on the target concept increased from pretest to posttest whereas the number of descriptive and practical answers decreased, thus suggesting a positive influence of collaborative experimentation on the students' conceptual knowledge. But the study suffered from a number of methodological weaknesses, particularly the lack of a control condition. Hence, definite conclusions with regard to the effectiveness of collaborative inquiry learning in chemistry cannot be drawn from the results.

Of the remaining studies we identified that dealt with collaborative learning in chemistry, two also used a one-group design (Fasching & Erickson, 1985; Towns & Grant, 1997), thus limiting conclusions with regard to the effectiveness of the approach under investigation. Hence, only two studies remain to be reviewed here. Basili and Sanford (1991) compared the number of misconceptions about conservation laws held by college students who had worked in small groups to the number of misconceptions held by students who had received traditional instruction for the same number of class periods. Their main finding was a lower proportion of misconceptions about conservation laws among the students in the treatment condition. The study thus showed that college students can benefit from collaboration in stoichiometry at the level of conceptual knowledge. Conflicting evidence was presented by Tingle and Good (1990). They did not find differences in problem-solving performance and conceptual understanding between a sample of high school students who had solved stoichiometry problems individually and a sample of students who had worked on the problems collaboratively. However, the study suffered from several drawbacks. Hence, the conclusions that can be drawn are subject to limitations.

Despite the scarcity and inconsistency of empirical findings there are reasons to assume that collaborative inquiry learning in chemistry can be effective with regard to the acquisition of conceptual knowledge. First of all, evidence from studies in mathematics (e.g. Moschkovich, 1996), physics (Ploetzner *et al.*, 1999), biology (Okada & Simon, 1997) and scientific experimentation (Teasley, 1995) indicates that collaborative learning (in face-to-face as well as in computer-mediated settings) can promote the acquisition of conceptual knowledge.

There also is a rich body of research on the mechanisms of learning during collaboration. Studies have shown that giving explanations is an important process with regard to learning during collaboration (Hausmann *et al.*, 2004; Okada & Simon, 1997; Webb, 1989). In a meta-analysis, Webb (1989) found that giving explanations has positive effects on learning and performance when the explanations are highly elaborate, the reason being that such explanations require active processing. Another mechanism that has been discussed in the literature is co-construction or joint production of knowledge (Berg, 1993, 1994; Hausmann *et al.*, 2004; Jeong & Chi, 1997). Berg (1993, 1994), for example, observed a significant positive correlation between joint production of knowledge during collaboration and subsequent algebra performance. Metacognitive activities such as planning, monitoring and reflection have also been found to contribute to learning during collaboration (e.g. Bielaczyc *et al.*, 1994).

While engaging in explanatory, co-constructive and metacognitive activities has proven to be important for knowledge acquisition and subsequent problem-solving performance they are not the only processes that constitute "good" collaboration. To create conditions under which mechanisms such as explaining can take effect the learners have to manage their interactions and organize themselves. The core process enabling effective interactions among the collaborating learners is coordination. It comprises aspects such as coordinating communication and interaction at the task level, the content level and the process level (Dillenbourg *et al.*, 1995; Meier *et al.*, 2007) and coordinating the collaborative activities with regard to attention, motivation, time and technology (Barron, 2000; Meier *et al.*, 2007).

Although there is empirical evidence of the effectiveness of collaborative learning in scientific disciplines and the mechanisms of learning during collaboration are well-understood, the implementation of collaborative (inquiry) learning in instructional contexts, be it a face-to-face or a computer-mediated one, does not guarantee learning. Left to their own devices, learners seldom engage in effective collaboration. Rather, they tend to deal with problems at the surface level only (e.g. Salomon & Globerson, 1989), arrive quickly at a shared solution instead of engaging in deep and meaningful interactions (e.g. Kerr *et al.*, 1996), insufficiently coordinate their interactions (e.g. Baker & Bielaczyc, 1995; Barron, 2000) and often fail to reach and maintain shared understanding (Baker & Bielaczyc, 1995).

Altogether, the claim that collaboration enhances the effectiveness of inquiry learning with computer simulations is justifiable as collaborative learning can promote the acquisition of conceptual knowledge through specific mechanisms and under certain conditions. Like individual inquiry learning, however, collaborative (inquiry) learning requires instructional support to unfold its potential benefits.

Collaboration scripts represent a means of instructional support that can enable and encourage the learners to engage in effective collaboration. Therefore, the following section deals with collaboration scripts.

2.4. *Instructional support for collaboration: Collaboration scripts*

Starting with the work of Dansereau (1988) and O'Donnell and Dansereau (1992), evidence has accumulated that collaboration scripts are an effective means of instructional support for collaboration. What are collaboration scripts? In the most general terms, collaboration scripts are sequences of activities arranged to prompt interactions among the learners that might not occur spontaneously or take an unproductive or even counterproductive form if unsupported (Kollar *et al.*, 2006). In her definition, King (2007) emphasizes the instructional nature of collaboration scripts: Collaboration scripts

> "describe how collaborative learning can be externally structured or scaffolded for the purpose of prompting group interaction that promotes learning. Scripting of the interaction during collaboration is designed so that the roles of participants, actions engaged in, and the sequence of events, prompt specific cognitive, socio-cognitive, and metacognitive processes, thus ensuring that the intended learning takes place." (p. 25)

The prompting of cognitive, socio-cognitive and metacognitive processes referred to by King in her above definition is often realized with conversation starters or prestructured questions, which the learners are instructed to use during collaboration. The conversation starters are designed to promote those processes known to underly effective collaborative learning, in particular elaborated explanations, knowledge co-construction and joint reflection (e.g. King, 1994; Teasley, 1997; also see Section 2.3).

Collaboration scripts have been studied extensively in face-to-face learning settings (for a comprehensive review, see Kollar *et al.*, 2006). Among the earliest examples of script-like instructional techniques developed and implemented in the classroom are the jigsaw approach by Aronson (1978) and the equally well-known reciprocal teaching approach by Palinscar and Brown (1984). Collaboration scripts for computer-supported (including computer-mediated) settings entered the research agenda towards the end of the past decade (cf. Kollar *et al.*, 2006). One of the first studies on scripting collaboration in computer-supported settings was that by Hron *et al.* (1997). Recent years have seen a surge in the number of studies published on collaboration scripts for computer-supported settings (e.g. Rummel & Spada, 2005b; Weinberger *et al.*, 2007).

Yet, very few studies among the large body of research on collaboration scripts are from the domain of chemistry. And as far as we are aware, none of these studies dealt with scripting collaboration in stoichiometry. One team of researchers has implemented and tested collaboration scripts for general chemistry.

Sumfleth *et al.* (2004a, 2004b) conducted a study involving 7th grade students. Small groups of students were given a number of materials, including a collaboration script that provided guidance on role distribution and turn taking among the collaborators. Compared to the students under the control condition, who were exposed to teacher-centered instruction during the six-lesson treatment phase, the students under the treatment condition acquired significantly more knowledge of chemistry. The difference in knowledge was yet stronger at follow-up, six months after the treatment. Walpuski (2006), who was a member of the Sumfleth team at that time, tested the effectiveness of two means of instructional support — structural support and error feedback. The structural support was designed to guide the collaborating learners through a sequence of activities similar to the process of scientific discovery. Walpuski's sample consisted of 320 German high school students. The results were not consistent with the findings reported by Sumfleth *et al.* (2004a, 2004b). Walpuski (2006) identified a significant main effect of error feedback but no effect of structural support, that is, the collaboration script. Altogether, the evidence available to date does not allow definite conclusions with regard to the effectiveness of collaboration scripts as a means of instructional support for collaboration in chemistry. There is a clear need for further research on scripting collaboration in chemistry, particularly in stoichiometry.

Evidence of the effectiveness of collaboration scripts comes, however, from other scientific disciplines (e.g. King, 1994) and from the domain of mathematics (Berg, 1993, 1994; Kramarski, 2004). Berg (1993, 1994), for example, developed a script to support collaborating learners in the domain of algebra. In her field study she asked pairs of high school students to interact as instructed by the collaboration script. The students of the control condition received teacher-centered instruction during the treatment phase. Berg found that the collaboration script had a positive effect on performance at posttest and at follow-up. Berg's findings are corroborated by Kramarski (2004). She found that learners who worked through a sequence of metacognitive activities gained more from solving math problems collaboratively than learners who did not receive that kind of instructional support for collaboration.

Since the publication of the first studies on collaboration scripts for computer-supported settings researchers have been voicing their concerns about the restrictiveness of collaboration scripts (see e.g. Hron *et al.*, 1997). In his frequently cited article, Dillenbourg (2002) argued that a balance needs to be obtained between structuring the interactions among the learners and allowing them to adapt the collaboration script to their needs. Dillenbourg introduced the term *over-scripting* to refer to the negative effects of imposing "one size fits all" structures on the learners' natural interactions and problem solving. The problem parallels the *assistance dilemma* (Koedinger & Aleven, 2007), which continues to be discussed in the literature on individual learning — whether to provide instructional support and, if so, when and to what extent. With regard to collaboration scripts as a means of instructional support for collaboration, adaptation may be a way out of the dilemma (Rummel & Weinberger, 2008). Adaptive collaboration scripts can meet the learners' needs without the risk of constraining their interactions in a non-beneficial way or impeding their problem solving.

So far little research has been conducted on adaptively scripting collaboration (Rummel & Weinberger, 2008). Gweon *et al.* (2006) investigated the effects of an adaptive collaboration script implemented in a computer-mediated learning environment in which pairs of students worked through complex math problems. The adaptive component of the script consisted of prompts that aimed at explanation, reflection and balanced participation. The results of the Gweon *et al.* study showed that the adaptive collaboration script influenced positively the quality of the students' collaboration and their individual learning outcomes. While the results were promising, the study also highlighted the need for further research into adaptive collaboration scripts. Our hope is that our work will contribute to closing this current gap in research on collaboration scripts.

3. Our Approach to Facilitating Learning from Computer-Supported Collaborative Inquiry

Research has shown that instructional support is necessary to ensure learning from inquiry in computer-based learning environments (e.g. de Jong & van Joolingen, 1998). Based on the empirical evidence available to date, collaborative learning constitutes a reasonable extension of computer-based inquiry learning environments. But collaborative learning has to be scaffolded for its mechanisms to take effect. Thus, when inquiry learning is extended to computer-supported collaborative inquiry learning the instructional support provided to the learners should be designed in such a way that (a) the learners engage in the central activities of the inquiry cycle (de Jong, 2005), (b) the learners show "good" collaboration, that is, engage in fruitful collaborative activities and (c) the learners' interactions (particularly their explanatory, co-constructive and metacognitive activities) are directed at their inquiry activities and at productive use of the simulations and cognitive tools offered to them.

The present state of research suggests that collaboration scripts can meet these demands (cf. Kollar *et al.*, 2006). We hypothesize that a promising approach to scripting computer-supported collaborative inquiry learning is to integrate structural and adaptive support. We developed such a collaboration script and partly incorporated it into the computer-based learning environment, which the learners used to carry out their collaborative inquiry activities.

3.1. *Structural support components*

A sequence of activities modeled on de Jong's (2006) inquiry cycle formed the backbone of the collaboration script. Hence, the script prompted the processes which are known to be important for learning from inquiry. We made sure, however, to phrase the script instructions (presented to the learners in the form of a booklet) in a way that emphasized the collaborative aspects of the activities, thus encouraging the processes responsible for learning during collaboration. In addition, the script instructions assisted the learners in using the computer-based learning environment productively by pointing out to them which component of the learning environment to use for which inquiry activity.

The inquiry activities were grouped into five phases (see Table 1): (1) brainstorming, (2) developing a strategy, (3) conducting experiments, (4) analyzing the experiments and (5) checking the solution. Apart from the first phase, all of the phases were designated as collaborative phases. We decided to place an individual phase at the beginning of the sequence of activities as research has shown that adding some individual activities to the joint activities instructed by collaboration scripts enhances the quality of interactions (Hermann *et al.*, 2001; Rummel & Spada, 2005a). Moreover, the central activity of the first phase was brainstorming. Empirical evidence indicates that collaborative brainstorming is less effective than individual brainstorming (Diehl & Stroebe, 1991), which provides further support for our decision to designate the first phase as an individual one.

In order to structure the learners' collaborative inquiry to a sufficient extent while at the same time being minimally coercive, the script instructions asked the learners to work through the phases once only, and left it up to them to decide on the order of activities within each phase.

At two points of the sequence of activities, the phases were supplemented by conversation starters that aimed at promoting co-construction and explaining — two of the mechanisms which have been found to contribute substantially to learning during collaboration (e.g. Hausmann *et al.*, 2004; King, 1994; Teasley, 1997). We assumed that those points, namely the beginning of the second phase and the beginning of the fourth phase, marked critical moments with regard to the learners' collaborative inquiry and required additional structural support. Therefore, the conversation starter at the beginning of the second phase encouraged learners to co-construct knowledge: "I think our ideas of how to solve the chemistry problem differ the most with regard to..." At the beginning of the fourth phase the learners were presented with a conversation starter prompting them to engage in explaining: "Looking at the results of our experiments I do not understand why..." The conversation starters were integrated into the computer-based learning environment.

3.2. *Adaptive support components*

The main adaptive support component of our collaboration script consisted of 34 prompts aimed at promoting effective collaboration and preventing ineffective interactions. We took both a top-down and a bottom-up perspective for the development of the *adaptive collaboration prompts*. First, we created a multi-level taxonomy of the major aspects of effective and ineffective collaboration to be found in the literature and constructed generic collaboration prompts based on the taxonomy. Second, we created a multi-level taxonomy comprising behaviors that we expected to occur frequently with high school students engaging in collaborative inquiry in

Table 1. Overview of the phases of the collaboration script.

Sequence of Activities	Components of the Computer-Based Learning Environment to be Used	Product to be Created by the Learners	Time Recommendation
Phase 1: Brainstorming			
(1) Read the problem description (2) Brainstorm about chemical concepts and principles relevant to the stoichiometric problem (3) Take notes on main ideas (4) Inform collaborator when done	Cognitive tool (note-taking and mind-mapping)	Summary of ideas	7 min
Phase 2: Developing a strategy			
(1) Read the conversation starter (2) Discuss differences and similarities between ideas (3) Develop a strategy for solving the problem and plan suitable experiments (4) Take notes on strategy	Cognitive tool (note-taking and mind-mapping)	Summary of strategy	7 min
Phase 3: Conducting experiments			
(1) Conduct three (max.) experiments and consider possible results (2) Take notes on main experimental results	Simulation (virtual chemistry laboratory), cognitive tool (note-taking and mind-mapping)	Notes on experimental results	7 min
Phase 4: Analyzing the experiments			
(1) Read the conversation starter (2) Discuss chemical concepts and principles with regard to the experimental results (3) Consider a solution to the problem (4) Take notes on the analysis and interpretation of the experimental results	Simulation (virtual chemistry laboratory), cognitive tool (note-taking and mind-mapping), calculator	Summary of results	10 min
Phase 5: Checking the solution			
(1) Write down the solution and have the experimenter check it	Cognitive tool (note-taking and mind-mapping)		3 min

the stoichiometry learning environment. In developing this taxonomy, we drew on the comments of chemistry teachers who had tested the learning environment, pilot tests involving high school students and observations we made while watching a number of learners work with the simulated chemistry laboratory VLab (the core component of the learning environment) during a previous study (Tsovaltzi *et al.*, 2008). Finally, we matched the generic collaboration prompts of the top-down taxonomy to the lowest-level categories of the bottom-up taxonomy and rephrased the prompts to maximize their relevance and clarity in the context of the stoichiometry learning environment. We had not expected the taxonomies to match perfectly as every system constitutes a specific learning setting, thus affording specific behaviors. Therefore, when a generic collaboration prompt did not match a category of the bottom-up taxonomy it was removed. When a category of the bottom-up taxonomy did not line up with any of the generic collaboration prompts we created a new prompt.

An example of a collaboration prompt, together with the branches of the two taxonomies linked to this prompt, is displayed in Figure 2 (please contact authors for a full list of the prompts and for the two taxonomies). This is how the example is to be decoded from the right: The research literature indicates that giving justifications, which is very similar to giving explanations (see Section 2.3), is one of the processes responsible for learning during collaboration (Okada & Simon, 1997). Therefore, the learners should be encouraged to explain to one another their rationale for proposing a particular experiment. And this is how the example is to be read from the left: The learners are engaging in a collaborative inquiry activity and focusing on the same section of the learning environment or on the same material. Next, it is observed that the learners are talking to one another. At a certain moment, one of the learners proposes to carry out an experiment. However, he does not explain or justify, for example by referring to a chemical concept, why they should carry out the experiment. Instead, he might say something like, "Let's mix some of the blue solution and some of the yellow solution and see what happens. How about 50 ml each?" The learners will then receive the collaboration prompt displayed at the intersection of the two taxonomies: "Before you conduct an experiment in the virtual laboratory explain to each other why you decided on this experiment." However, the prompt will be delayed until the collaborators plan a second experiment without a theoretical rationale. With the exception of some severe instances, one-time observations do not trigger prompts immediately so that the learners remain in charge of their collaboration and are allowed time to monitor and regulate their behavior on their own.

The second adaptive support component of our collaboration script consisted of six prompts that were to safeguard *fidelity to the script*, or more precisely, fidelity to the sequence of activities described in the preceding section. The overall purpose of the script was to provide instructional support to the learners while minimizing the risk of over-scripting. Therefore, fidelity to the script was not enforced but

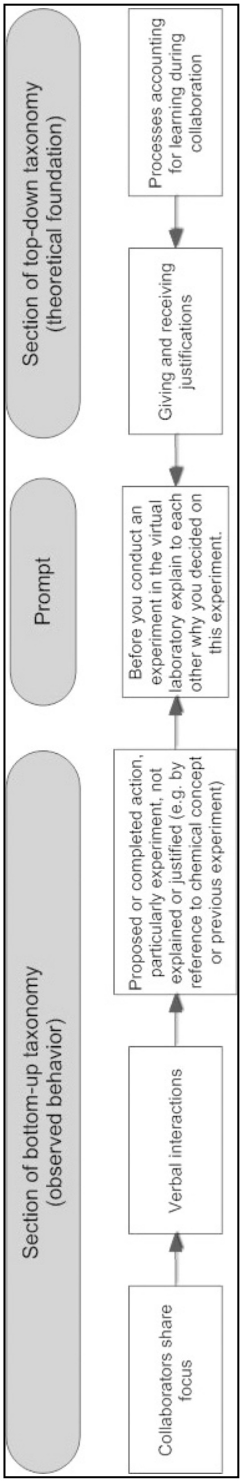

Figure 2. Example of adaptive collaboration prompt.

prompted in an adaptive fashion when the learners lingered on an activity, skipped an important activity altogether or showed trial-and-error behavior.

The third adaptive support component of the script was a set of hints designed to provide *support for experimentation* at the strategic and conceptual levels. We incorporated this minimum amount of domain-specific support into the script in order to ensure that the collaborating learners did not fail to learn because of a dead-end problem-solving path, severe errors in their experimental design or continuous trial-and-error behavior.

All of the adaptive support components were implemented in a *Wizard of Oz* fashion in this first exploratory step of our work. The collaborating learners were made to believe that their actions in the computer-based learning environment and their verbal interactions were being monitored by a computer program. But in fact, a confederate to the experimenter (wizard) worked behind the scenes. The wizard observed the learners' collaborative inquiry activities in the computer-based learning environment. When she observed a lack of effective collaboration or the occurrence of ineffective interactions, as specified in the bottom-up taxonomy, she sent a prompt or hint that appeared on the learners' screen.

4. Research Questions

The collaboration script described in the previous section was designed to enhance collaborative inquiry learning when using the simulated chemistry laboratory VLab (http://www.chemcollective.org/applets/vlab.php). The collaboration script, the simulation and a cognitive tool (see Section 5.3 for details) formed a prototype learning environment. The prototype was computer-based with the exception of one component of the collaboration script (i.e. the sequence of inquiry activities). In the exploratory study reported in this paper, we conducted a full empirical test run with the prototype comparing a scripted collaboration condition to an unscripted one. The results of the study will guide our efforts of improving the collaboration script and inform the next iteration of our learning environment. Towards this end, we aimed at assessing the benefits of the learning environment and the added value of the collaboration script, understanding which factors contribute to the effectiveness or ineffectiveness of our approach to scripting, and identifying features of the learning environment that might hinder productive collaboration and inquiry. The study also served the purpose of exploring the particular needs of the target population (German high school students) with respect to stoichiometry learning. We tried to answer the following research questions:

- Can learners benefit from working collaboratively on a stoichiometry problem using the learning environment with regard to procedural and conceptual knowledge of stoichiometry?
- Which features of the learning environment enable or hinder productive collaboration and inquiry?

- Do learners who are supported by a collaboration script, which combines structural and adaptive support (as described above), benefit more from using the learning environment than learners who are not supported by such a script?
- How does the collaboration script influence learners' collaborative inquiry and problem-solving efforts?
- Which script components, features of the simulation and learner characteristics enhance or impede the effectiveness of the collaboration script?
- Is the current implementation of the collaboration script (non-adaptive structural support, low degree of coerciveness of both structural and adaptive support, computer-based with one paper-based component) conducive to learning?
- Does the support provided by the collaboration script meet the needs of the target population?

5. Method

5.1. *Participants*

A total of 54 students from 12 high schools[1] in the south-west of Germany, aged 15 to 18 years ($M = 16.60, SD = 0.74$) participated in the study. Twenty-nine of the participants were female. Participation in the study was voluntary. The students were allowed to name a friend or classmate to be paired up with for the study. Those who did not name a friend or classmate were paired up with another student by the experimenter. Every participant received 20 Euros for taking part in the study.

We excluded three of the 27 dyads that participated in the study from the main data analysis. Two of the dyads stood out as outliers with regard to the number of chemistry courses they had taken and their learning outcomes respectively. The third dyad was excluded because of irregularities in the experimental procedures and because one of the two students dropped out before the end of the experiment. Thus the final sample included 24 dyads.

5.2. *Design*

The dyads ($n = 24$) were randomly assigned to two conditions. Under the *scripted collaboration condition* ($n = 12$ dyads), the dyads were assisted by the collaboration script. Under the *unscripted collaboration condition* ($n = 12$ dyads) the dyads were not assisted by the collaboration script. To ensure equal opportunities for learning under both conditions, the dyads of the unscripted collaboration condition were given descriptions of the computer equipment, programs and files available to them during the learning phase as well as a set of general experimentation hints (e.g. "Were the samples of zinc you used in your experiments large in enough for a reaction to occur?"). Both of these collaboration script substitutes were non-adaptive.

[1] More precisely, all of the students attended a *Gymnasium* at the time of the study. In the German education system, the *Gymnasium* is the type of high school that prepares students for college.

The duration and procedures of the experiment were identical for both conditions. Every participant took an individual knowledge posttest. We also collected data on the participants' prior knowledge of stoichiometry, their attitudes toward collaboration, their academic achievement in chemistry and mathematics and the number of chemistry courses they had taken.

5.3. *Learning environment*

During the learning phase, the dyads of both conditions worked on a stoichiometry problem (see Section 5.4) in a computer-based learning environment. The main component of the learning environment was the simulated chemistry laboratory VLab described in the background chapter (see Figure 1). Its interface includes a workbench, the stockroom and the information window. The information window displays, for example, volume and molarity (see Figure 3).The other components of the learning environment were Microsoft Office PowerPoint, which we set up to function as a simple cognitive tool providing note-taking and mind-mapping functionality, and an on-board calculator. The components of the learning environment operated independent of one another. A dual-monitor setup allowed the dyads to simultaneously view the virtual chemistry laboratory and the other tools.

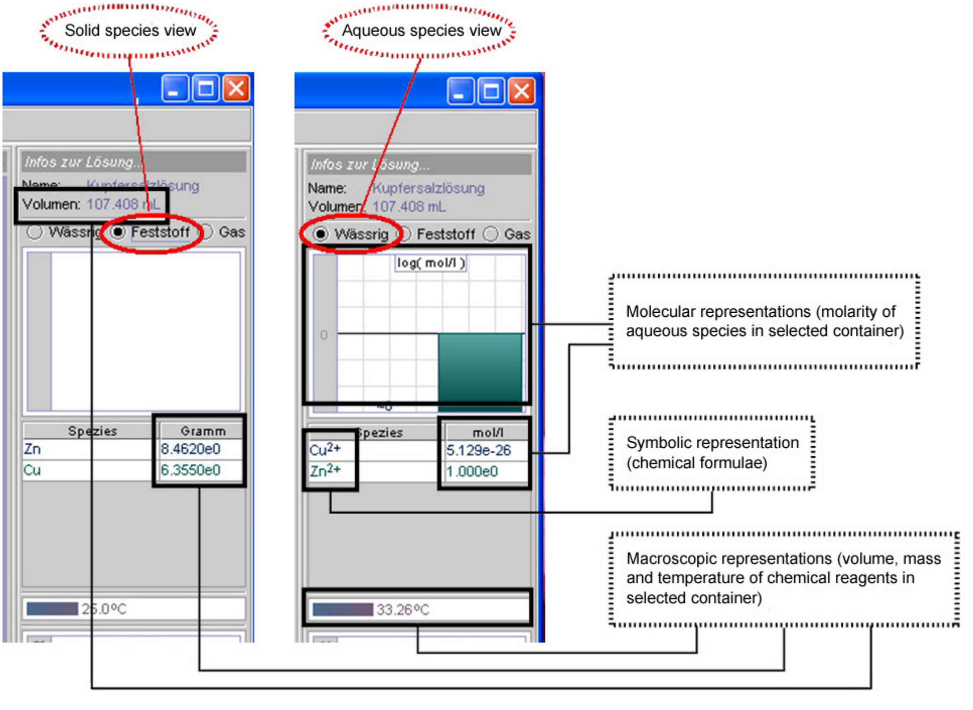

Figure 3. Annotated screenshots of the information window of the simulated chemistry laboratory *VLab* (http://www.chemcollective.org/applets/vlab.php).

5.4. *Task for collaborative inquiry*

The stoichiometry problem the dyads worked on during the learning phase asked them to identify the chemical reaction of copper sulphate and zinc, to formulate the chemical equation and to produce 20 grams of copper. The sample of copper was to be free of zinc residues. The stockroom of the virtual chemistry laboratory contained copper sulphate solution and zinc powder for the dyads to use in their experiments. The dyads were given information about the molarity of the copper sulphate solution, the ionic charge of copper sulphate and the molar mass of copper and zinc. They were also provided with a small chemistry glossary, which contained, for example, an entry on molar mass.

5.5. *Experimental setup and procedures*

The setup included both a collaborative workstation and an individual workstation. The wizard was seated at a separate workstation in the laboratory. Under the unscripted collaboration condition the dyads were not required to use the individual workstation and the wizard's computer was turned off.

All of the experiments were carried out by the same experimenter. Also, one person (a graduate student with substantial experience in scaffolding student learning in the domain of chemistry) served as the wizard in all of the experiments. Following the instructions about the experiment, the participants engaged in three preparation activities: They (1) individually read a text about key stoichiometric concepts, (2) they watched two short videos on the computer-based learning environment and (3) they collaboratively worked on two tasks to familiarize themselves with the virtual chemistry laboratory and the note-taking and mind-mapping tool. After the preparation phase, participants took an individual knowledge pretest (10 minutes, time on task controlled by the experimenter). After a short break, the dyads were given detailed instructions about the learning phase. They were told they had 50 minutes to work on the stoichiometry problem and three chances of submitting the correct solution. Each of the learners was given a description of the stoichiometry problem. When the learners had read the description the experimenter announced the beginning of the learning phase and handed each of the learners a booklet that contained instructions on the phases of the collaboration script (scripted collaboration condition) or descriptions of the computer equipment, programs and files available during the learning phase (unscripted collaboration condition). The booklets also contained a small chemistry glossary and a set of hints on how to use the software, more specifically the virtual chemistry laboratory.

Under the scripted collaboration condition, the procedures for the learning phase were as follows: During the first cycle, participants followed the collaboration script (see Table 1). After the first cycle, they were free to choose which activities to engage in. At the beginning of the first cycle, each learner was seated at one of the workstations. After the learners had completed the first phase of the script, they received technical support from the experimenter in initiating the transitional phase. This also functioned as an activation signal to the wizard. After 40 minutes, the experimenter announced the time remaining of the learning phase. The dyads were free to decide when they wanted to submit a solution. When they indicated they had solved the stoichiometry problem the experimenter checked the dyad's solution and gave standardized feedback. Under the unscripted collaboration condition, learners jointly decided whether and how to use the two workstations. They were given technical support if needed. After 25 minutes, the learners were handed the experimentation hints (see Section 5.1). The procedures otherwise followed those under the scripted collaboration condition.

After a short break, participants individually filled in the remaining questionnaires (attitude questionnaire, evaluation questionnaire) and took the individual knowledge posttest (30 minutes, time on task controlled by the experimenter). Then they were interviewed about their experience during the study, debriefed and paid for their participation. The total duration of the experiment was three hours.

5.6. *Instruments*

We developed a test to assess participants' knowledge of stoichiometry at posttest. Participants were given a calculator together with the test and were allowed to work on the items in the order indicated for 30 minutes. The knowledge posttest consisted of eight free-response problem-solving items, which were subsumed under two scales: Four of the problem-solving items made up the procedural scale; four items made up the conceptual scale. The conceptual problem-solving items covered all of the concepts that we expected participants' to learn about from working on the stoichiometry problem. The procedural problem-solving items covered basic stoichiometric procedures such as calculating mass and amount of substance. While these items did not require conceptual knowledge, participants holding correct and adequate conceptual knowledge were likely to be more successful in solving them.

We also assessed participants' prior knowledge of stoichiometry. The knowledge pretest was made up of three free-response problem-solving items (one conceptual, two procedural), which paralleled the first three items of the knowledge posttest. The time that participants could spend working on the knowledge pretest was limited to 10 minutes.

The procedural problem-solving items and the conceptual problem-solving items of the knowledge tests were analyzed separately. Performance on the procedural problem-solving items was rated on a three-point scale, with two points indicating a correct solution, one point indicating an incorrect solution and zero points indicating the item was not answered at all or the answer was unrelated to the problem description. Performance on the conceptual problem-solving items was rated on a four-point scale to allow for discrimination of answers that consisted of a partially correct solution and answers that were incorrect and/or marked by severe conceptual errors, that is, errors indicating insufficient knowledge of the theories and principles underlying stoichiometry. Thus, correct solutions received three points, partially correct solutions received two points, incorrect solutions and answers that contained two or more conceptual errors received one point. Again, blanks and answers that did not relate to the problem description resulted in zero-point ratings.

Socio-demographic data and information on their academic achievement and the number of chemistry courses they had taken were provided by the participants prior to their participation in the study.

The attitude questionnaire that we used to assess participants' attitudes toward collaboration was a translated and slightly modified version of the *Social Interdependence Scales* (cooperative interdependence, individualistic interdependence, competitive interdependence) by Johnson and Norem-Hebeisen (1979). The attitude questionnaire was preceded by a questionnaire assessing the participants' evaluation of several aspects of the study. It combined one global (overall evaluation of the experiment) and three specific scales (collaboration, learning environment, instructional support). Participants were asked to provide their answers to the attitude questionnaire and the evaluation questionnaire on a six-point scale, ranging from *not at all true* to *completely true*.

Furthermore, we took screen and audio recordings during the learning phase of the experiments and interviewed participants about their experience during the study at the very end of the experiments.

6. Results and Discussion

6.1. *Learning outcomes — Implications for the design of the stoichiometry learning environment and the collaboration script*

The participants of both conditions showed weak performance on the conceptual problem-solving items of the posttest, scoring less than half of the maximum total on average (see Table 2). Despite stronger average performance on the procedural problem-solving items, the learning outcomes achieved in our study have to be considered low. It could be argued that the knowledge posttest went beyond the level of understanding that could be achieved from working on a single stoichiometry problem in the learning environment when starting from the participants' level of prior knowledge and general academic achievement. However, participants' average performance on the knowledge pretest did not indicate a floor effect and, hence, a complete lack of prior knowledge in stoichiometry. Many participants failed to solve the

Table 2. Mean scores on the knowledge posttest scales by condition controlling for prior knowledge of stoichiometry.

	Scripted Collaboration		Unscripted Collaboration	
	M	*SD*	*M*	*SD*
Conceptual problem-solving items	5.07	0.48	4.84	0.48
Procedural problem-solving items	5.83	0.29	6.13	0.29

Note: The maximum total for the conceptual problem-solving items was 12 points. The maximum total for the procedural problem-solving items was 8 points.

conceptual problem-solving items and arrived at partially correct solutions to the procedural problem-solving items (at pretest as well as at posttest) because of what seemed to be deficiencies in basic algebra skills (e.g. transforming fractions). The high to medium correlations among posttest performance and academic achievement in mathematics (conceptual problem-solving items: $r = 0.57$, $p < 0.001$; procedural problem-solving items: $r = 0.38$, $p < 0.01$) provide support to this conclusion. As we had assumed that students from the target population possessed sufficient knowledge of algebra and as we had designed the stoichiometry problem accordingly, participants' low-level algebra skills might have impeded their learning. Hence, our findings suggest that success in solving stoichiometric problems does not depend only on conceptual knowledge of chemistry, as concluded from previous studies (e.g. BouJaoude & Barakat, 2003; Schmidt, 1990, 1992), but also on basic algebra skills. This is in line with Gabel and Bunce's (1994) conceptualization of stoichiometric problem solving as solving "chemistry problems involving mathematical reasoning skills" (p. 301). Hence, in future iterations of our stoichiometry learning environment we have to take into account students' prior knowledge beyond the focal learning domain and accommodate deficiencies in the adjacent domain of algebra. This could be realized, for example, by including instructional units on the computational aspects involved in stoichiometric problem solving. Van Merriënboer *et al.*'s (2002) model of instructional design could then form the framework for the design of the learning environment. The model specifies how learning environments should be designed to facilitate the acquisition of skills that have to be coordinated when solving complex problems. Stoichiometry problems constitute complex problems and solving them requires skills such as identifying relevant chemical concepts, determining the quantities consumed and produced by chemical reactions, formulating equations and carrying out algebraic procedures. According to the Van Merriënboer *et al.* model, learning environments used to train such complex problem-solving skills should be made up of four components: (1) a variety of authentic *learning tasks* grouped into task classes and ordered in simple-to-complex sequences; (2) *part-task practice* for low-level procedural skills, that is, sets of practice items that are interspersed among the learning tasks; (3) continuous availability of *supportive information*, that is, resources (e.g. cognitive strategies) for solving classes of learning tasks; (4) *just-in-time* (JIT) *information* (e.g. information displays), that is, information relevant to a set of practice items which is presented to learners before they work on the items. When applying the Van Merriënboer *et al.* model to our stoichiometry learning environment we would maintain the sequence of learning activities specified by the collaboration script but supplement it with part-task practice and JIT information.

The participants of the two conditions did not differ significantly with regard to prior knowledge of stoichiometry, attitudes toward collaboration, academic achievement in chemistry and mathematics and number of chemistry courses taken. Hence, the subsamples can be considered comparable. A one-way multivariate analysis of covariance (MANCOVA) with procedural and conceptual problem-solving performance at posttest as the dependent variables and prior knowledge of stoichiometry (measured by the pretest) as the covariate did not yield significant differences between the scripted collaboration condition and the unscripted collaboration condition, $F(2, 20) = 0.465$, n.s., $\eta^2 = 0.04$. Thus, it seems that the dyads of the scripted collaboration condition did not benefit more from solving the stoichiometry problem than the dyads of the unscripted collaboration condition that did not receive instructional support for collaborative inquiry learning. This result suggests that scripting collaborative inquiry does not enhance stoichiometry learning — a finding contrary to studies reporting positive effects of collaboration scripts on learning in science and mathematics (e.g. Berg, 1993, 1994; King, 1994; Kramarski, 2004). Several factors might have contributed to the ineffectiveness of the collaboration script in our study, all of which implicate modifications of our approach to scripting and improvements of the design of the stoichiometry learning environment.

First, the participants had never encountered a collaboration script. Thus, applying the script might have increased cognitive load during the learning phase (cf. Dillenbourg, 2002; Gweon *et al.*, 2006). Training students on how to use the collaboration script prior to the learning phase might prove effective (cf. Rummel & Spada, 2005). However, we consider turning the paper-based component of the collaboration script into a technology-enhanced component a more promising approach. If the sequence of inquiry activities, which was instructed on paper in our initial prototype, was implemented via the interface of the virtual chemistry laboratory the amount of structural support provided could be adapted to the collaborators' changing needs (cf. Diziol *et al.*, 2010). Furthermore, the support could then be faded out as the collaborators internalize the script instructions (cf. Wecker *et al.*, 2010). This would move the stoichiometry learning environment further along the line toward a system providing adaptive support for collaborative inquiry learning.

Second, we observed that most of the dyads spent more time on calculations than on discussing chemical concepts and stoichiometric principles during Phase 4. Hence, although the collaboration script targeted explanatory activities, participants tended to focus on carrying out procedures. This suggests that the collaboration script has to be modified to focus students on the concepts and principles underlying the stoichiometry problem. Phase 4 of the collaboration script could, for example, be split and specify two roles. In Phase 4a, one of the collaborators would be assigned the task of explaining and drawing conclusions. The other would be assigned the task of monitoring the explanations for adequacy and completeness. In Phase 4b, one of the collaborators would perform the calculations required to solve the stoichiometry problem. The second role would involve monitoring the calculations and checking the solution against the explanations constructed in Phase 4a.

Third, the demands involved in relating the multiple external representations in the virtual chemistry laboratory might have rendered the collaboration script ineffective. The information window of the virtual chemistry laboratory holds multiple external representations (Figure 3) that differ in their form (text, graphics) and in the level at which they represent matter and the chemical processes it is subject to (macroscopic level, microscopic level, symbolic level). Coordinating and integrating the information from separate representations can be considered one of the most difficult tasks when learning with multiple external representations in any knowledge domain (Ainsworth, 2006). In the case of the virtual chemistry laboratory, the difficulty of relating the representations is increased by the fact that understanding the interrelatedness of the macroscopic level, the microscopic level and the symbolic level is essential to stoichiometric problem solving but a challenge in itself, regardless of the design and functions of the representations. As Gabel (1998) pointed out, one of the chief reasons why many high school and college students fail to solve chemistry problems is the difficulty of understanding the interrelatedness of the three levels of representation. In fact, participants' answers in the interviews and the chemistry teachers' comments on the virtual chemistry laboratory pointed toward the complexity of the data displays. With our collaboration script, the challenge was exacerbated by the absence of instructional support for relating representations. When redesigning the collaboration script we will, therefore, include scaffolding for interrelating the different representations in the simulation. The literature on supporting connection-making between multiple representations demonstrates that promoting active integration activities on the part of the students is crucial for learning (e.g. Bodemer & Faust, 2006; Bodemer *et al.*, 2004). This means, that the redesigned collaboration script should prompt learners to explain the different representations and their interrelations to one another. Prompts for connection-making alone, however, are not sufficient. The system should support students by dynamically linking representations and thus highlighting relevant relations (Van der Meij, 2007). Furthermore, it was found that support for interrelating representations should focus on deep, structural relations rather than surface features (Seufert & Brünken, 2006).

6.2. *Learning processes — Instructional design, interface design and interaction design implications*

In addition to our quantitative data analyses, we carried out a detailed qualitative analysis of two selected cases from the scripted collaboration condition. By analyzing the screen and audio recordings taken during the learning phase of the experiments we gained insights into the processes that occurred during the learning phase. This allowed us to extend and refine the design implications drawn from the quantitative results. The qualitative analysis was exploratory and guided by a set of questions. The questions focused on the following aspects: (1) The quality of the learners' collaboration, (2) the effects of the collaboration script on the learners' interactions and their joint attempts at solving the stoichiometry problem and (3) the learners' reactions and fidelity to the collaboration script. In particular, we were interested to see whether the dyads accepted the adaptive support and whether their collaboration improved following the prompts and hints.

We selected one dyad (Sio and Adi[2]) for the qualitative analysis that had shown below-average performance at pretest but above-average performance at posttest, both on the conceptual problem-solving items and on the procedural problem-solving items. In the second dyad (Sun and Mia), the pattern was reversed: They had achieved above-average scores at pretest but showed below-average performance at posttest. These patterns of prior knowledge and learning outcomes suggested to us that Sun and Mia had learned less from working on the stoichiometry problem despite script support than Sio and Adi.

6.2.1. *Sio and Adi: Successful learning despite difficulties in understanding*

Table 3 shows how Sio and Adi structured their learning phase. The table also displays the episodes central to their collaborative inquiry and problem solving as well as the prompts and hints given to them by the wizard.

To reveal the outcome of the dyad's efforts up front: Sio and Adi were not successful at solving the stoichiometry problem even though they conducted a number of crucial experiments and drew some correct conclusions. The problem was that they often failed to take into account all of the information available in the virtual chemistry laboratory when analyzing the results of their experiments. During the episode beginning at 39:29 minutes, for example, they did not take into consideration the information on the solid species. Adi even uttered his incomprehension given the "disappearance" of the solid species they had added to a beaker: "I can't believe there's nothing in it!" (translation by the authors) In fact, we observed the same difficulty with several dyads. In the virtual chemistry laboratory, aqueous species and solid species are displayed on different tabs. But these tabs were easy to miss and several dyads seemed to consider one of the tabs only. Thus, we assume the design of the virtual chemistry laboratory posed an unnecessary challenge to the students. This makes improvements of the interface and interaction design of the virtual chemistry laboratory paramount.

However, Sio and Adi experienced difficulties beyond usability issues. Both students showed deficiencies in their understanding of the chemical composition and the role of one of the substances involved in the chemical reaction. A similar lack of understanding of general chemistry concepts emerged with many dyads, indicating that at least some students require more domain-related instructional support than we had provided. As with the deficiencies in basic algebra skills, we suggest instructional units be added to the stoichiometry learning environment. If the general design of the learning environment was refined based on the Van Merriënboer *et al.* (2002) model of instructional design, as suggested in Section 6.1, this could be realized by *supportive information* that students can access when needed. In addition, we plan to implement a macro-assessment of students' knowledge of general chemistry concepts prior to their collaborative inquiry in the stoichiometry learning

[2]The participants are given fake names to increase the readability of the following text.

Table 3. Sio and Adi: Overview of time spent on phases, important episodes, prompts and hints given by the wizard.

Phase	From–to (min)	Onset of Episode	Short Description of Episode	Prompt Given by Wizard
Phase 1 (brainstorming)	(17:03 min)		(individual work)	
Transitional phase (exchanging ideas)	17:04–19:10 (2:06 min)		(individual work)	
Phase 2 (developing a strategy)	19:11–29:53 (10:42 min)	25:59	The wizard gave a collaboration prompt: The dyad then compared their summaries of ideas and considered both in their joint strategy.	"It is important that each of you contributes some of the ideas you came up with during the first phase to your joint strategy."
Phase 3 (conducting experiments)	29:54–end of learning phase (approx. 20 min)	30:48	The dyad conducted a crucial experiment and made a joint attempt at understanding the result. However, they failed to draw a definite conclusion.	
		39:09	Experimentation hint: It cannot be evaluated whether the dyad processed this hint.	"Discuss with your partner whether the sample of zinc you used in your experiment was large enough for a reaction to occur."
		39:29	The dyad conducted a crucial experiment but failed to draw an adequate conclusion. They had not taken into consideration the information on the solidspecies.	
		42:29	The dyad compared two samples obtained from the same experiment and drew a correct conclusion with respect to the solid species.	
		43:24	Fidelity-to-script prompt: The dyad ignored the prompt.	"Remember to take notes on the results of your experiments."
		46:30	Experimentation hint: The dyad resorted to trial-and-error experimentation.	Same as at 39:09.

environment. Based on their performance on the macro-assessment, the collaborating learners' attention will then be directed to specific supportive information units. Such a macro-assessment would take us yet another step closer toward a system providing adaptive support for collaborative inquiry learning in stoichiometry. A similar approach was taken by Walker *et al.* (2010): In their computer-supported collaborative learning system, help resources were made available to learners on the basis of an on-line assessment of their behaviors.

Concerning their collaboration, Sio and Adi showed effective behavior for the most part of the learning phase. Each of the two gave many explanations to his collaborator, they co-constructed some explanations and — in general — they coordinated their interactions well. During the second phase (developing a strategy), for example, Sio explained to Adi why some of his ideas from the first phase were incorrect; Adi in turn explained why his calculations were correct; then the collaborators co-constructed a chemical equation. However, it has to be pointed out that most of the explanations that Sio and Adi gave or co-constructed did not refer to theoretical concepts, stoichiometric principles or processes, therefore having to be described as shallow. This observation reinforces our previous suggestion of splitting some of the phases of the collaboration script and assigning roles to the collaborators to promote certain cognitive and metacognitive activities. By redesigning our collaboration script to separate conceptual activities from procedural activities (in the case of Phase 2, discussing concepts and planning experiments), we hope to be able to increase the number of deep explanations constructed by the collaborating learners.

Yet, the quality of this dyad's collaboration is reflected in the low number of prompts they received from the wizard. The only collaboration prompt they received seems to have influenced their collaboration in a positive way: At 25:59 minutes, Sio and Adi were reminded to integrate their ideas from the previous phase while developing a joint strategy. They studied this prompt and responded to it by comparing their notes and writing down a joint strategy using ideas from both summaries.

While they readily took up the adaptive support provided through the collaboration prompt, Sio and Adi showed low fidelity to the structural components of the collaboration script: They spent approximately 17 minutes on the first phase, which is more than twice the time that was suggested in the instructions. They never clearly transitioned from the third phase (conducting experiments) to the fourth phase (analyzing the experiments). And they did not take any notes beyond the first ones on their joint strategy. On the one hand, this shows that Sio and Adi benefited from the low degree of coerciveness of the collaboration script as it allowed them to adapt the structural support to their needs. On the other hand, they missed the opportunities for learning offered in the fourth phase by not observing the sequence of inquiry activities and neglecting the conversation starters. In particular, taking notes on the results of their experiments (as instructed by the script) might have helped them in planning a more thought-out series of experiments, thus increasing the effectiveness and efficiency of their inquiry.

In conclusion, the design of the collaboration script has to strike a balance between imposing structure on the learners, which seems necessary given the typically low quality of their collaborative inquiry, and allowing the learners to adapt the support to their needs. Turning the structural support components into adaptive support components, hence creating a completely adaptive collaboration script, might solve the "scripting dilemma". We suggest to macro-adapt the structural support, for example based on the learners' prior experience with collaborative inquiry learning, as it ensures that the learners' collaborative inquiry activities are effective from the very start.

6.2.2. *Sun and Mia: Failing in learning despite adaptive support*

Table 4 shows how Sun and Mia structured their learning phase. The table also displays the episodes central to their collaborative inquiry and problem solving as well as the prompts and hints given to them by the wizard.

Like Sio and Adi, Sun and Mia were not successful at solving the stoichiometry problem. They conducted crucial experiments but failed to interpret the results correctly, particularly the data displayed in the information window of the virtual chemistry laboratory. Moreover, it was striking that they continuously used distilled water and the Bunsen burner despite receiving experimentation hints from the wizard encouraging them to reconsider their experimental strategy.

Concerning their collaboration, Sun and Mia more or less coordinated their interactions well. But their behavior was largely ineffective with regard to the processes accounting for learning during collaboration. At the beginning of the second phase (developing a strategy), for example, Mia correctly argued that heating might not be a correct procedure; Sun did not take up this objection but suggested to move on and carry out the procedure in a trial-and-error fashion. This episode is an example of the many similar episodes that we observed with this dyad. For the most part of the learning phase, Sun did not acknowledge and join in Mia's attempts at constructing explanations. Even when Sun and Mia engaged in co-construction, their reasoning and consensus building remained superficial.

Sun and Mia received two collaboration prompts from the wizard. At the beginning of the third phase (conducting experiments), the wizard sent a collaboration prompt because Sun demonstrated ineffective behavior by ignoring Mia's attempt at constructing an explanation. Sun and Mia studied the prompt and responded to it by explaining to one another. However, the explanations were shallow. In addition, Mia did not take up Sun's objections which led the wizard to send yet another collaboration prompt. Sun and Mia ignored this prompt — just like they ignored the four experimentation hints they were given.

The dyad's fidelity to the structural components of the collaboration script can be described as moderate. Sun and Mia engaged in the inquiry activities of the first three phases as instructed and then departed from the sequence of activities and the corresponding instructions.

Table 4. Sun and Mia: Overview of time spent on phases, important episodes, prompts and hints given by the wizard.

Phase	From–to (min)	Onset of Episode	Short Description of Episode	Prompt Given by Wizard
Phase 1	(8:54 min)		(individual work)	
Transitional phase	8:55–10:54 (1:59 min)		(individual work)	
Phase 2	10:55–17:36 (6:41 min)	13:49	The wizard gave a fidelity-to-script prompt: The dyad then took notes on their strategy. But their consensus building was superficial.	"It is important that you develop a joint strategy and take notes on it before you move on to phase 3 (conducting experiments)."
Phase 3	17:37–24:53 (7:16 min)	21:48	Collaboration prompt: The dyad then engaged in shallow explanatory behavior.	"Explaining to one another the results of your experiments will help you in solving the stoichiometry problem."
		22:50	Collaboration prompt ignored.	"It is important that you take up your partner's questions and objections."
Phase 4	24:53–26:43 (1:50 min)			

Table 4. (*Continued*)

Phase	From–to (min)	Onset of Episode	Short Description of Episode	Prompt Given by Wizard
Free choice of activities	26:44–end of learning phase (approx. 24 min)	29:37	Experimentation hint ignored.	"Explain to one another why you used distilled water in your experiments and what happened when you added distilled water."
		30:29	Experimentation hint ignored.	"Think about the tools you have been using in your experiments and explain your reasoning to your partner."
		31:19	The dyad conducted a crucial experiment but failed to correctly interpret the result and draw an adequate conclusion.	
		37:46	Experimentation hint ignored.	"Remember that you are not going to learning much from trial and error. It is important that you think about what the results of your experiment might be before you carry it out."
		43:30	Experimentation hint ignored.	Same as at 29:37.
		43:23	The dyad conducted a crucial experiment and made an important observation regarding the products obtained. However, they drew incorrect conclusions from their observation.	

The case study of Sun and Mia highlights the importance of ensuring fidelity to both the structural and the adaptive components of the collaboration script. Sun and Mia missed the opportunities for learning offered in the fourth phase. It seems possible that they were not aware of their need for structural support or did not perceive the activities specified by the collaboration script to be of use in their joint efforts of solving the stoichiometry problem. They also ignored almost all of the prompts and hints they were given. As a consequence, the quality of their collaborative inquiry hardly improved during the learning phase. Two additions to the collaboration script could increase learners' awareness of their need for instructional support and help them understand the benefits of scripted collaboration. First, building on our previous suggestion of assessing prior experience with collaborative inquiry learning before the learning phase and macro-adapting the structural support to learners' needs, we propose to feed the results of the assessment back to the learners. Second, we suggest that informed training (Brown *et al.*, 1981) precedes the learning phase. The informed training could take the form of an instructional unit placed after the initial assessment of collaboration and inquiry skills or the form of links to explanations. The links would be provided with the prompts and hints. Although the option of following the links bears little risk of decreasing motivation it will probably be less effective than a mandatory instructional unit as learners are likely to ignore the links together with the adaptive prompts, particularly as they move towards the middle of the learning phase. Another option would be to block the interface of the learning environment for a certain time after a prompt or hint was given. However, this is likely to decrease motivation and result in behavior similar to what is known as *gaming the system* in research on intelligent tutoring systems (e.g. Baker *et al.*, 2008): Some learners will simply wait until the system restrictions are released instead of processing the prompts and hints. Therefore, we advocate feedback on collaboration and inquiry skills and informed training.

6.3. *Evaluation of the experiment — Implications for the implementation of the collaboration script*

The participants gave positive ratings to their experience during the study. For all of the four scales (overall experience, learning environment, instructional support, collaboration) the average ratings were above the mean of the rating scale. Descriptively, the dyads of the unscripted collaboration condition rated the overall experience, the instructional support they received and their collaboration more positive than the dyads of the scripted collaboration condition. However, these differences did not reach statistical significance (see Table 5). This pattern was reversed in the ratings of the learning environment, but again only descriptively (see Table 5). The somewhat higher ratings of the learning environment under the scripted collaboration condition probably constitute a novelty effect — the participants seemed utterly impressed with the adaptive prompts which they believed were generated

Table 5. Mean evaluation of the experiment by condition.

	Scripted Collaboration		Unscripted Collaboration			
	M	*SD*	*M*	*SD*	$t(22)$	*p*
Overall experience	4.58	0.29	4.78	0.46	−1.32	n.s.
Computer-supported learning environment	4.62	0.59	4.72	0.77	−0.36	n.s.
Instructional support (collaboration script or substitute)	4.00	0.73	3.88	0.99	0.34	n.s.
Collaboration	3.83	0.80	4.35	0.68	−1.70	n.s.

Note: Participants provided their answers on a six-point scale ranging from *not true at all* (1) to *completely true* (6).

based on an innovative computer algorithm. Based on comments made in the end-of-session interviews and on our observations during the learning phase, we assume that the dyads of the scripted collaboration condition tended towards lower ratings of the instructional support because they did not perceive the collaboration script to be useful, particularly as they progressed in the inquiry cycle. This could also explain why they were slightly less satisfied with their collaboration and enjoyed the experiment a bit less than the dyads of the unscripted collaboration condition. We assume that the perceived value of scripted collaboration influences learners' acceptance of script support, which in turn affects learning processes and outcomes (as seen in the two case studies). Therefore, we will need to ensure that learners recognize the usefulness of the collaboration script in the next iteration of the stoichiometry learning environment. We believe this can be achieved by improving the implementation of the collaboration script. Therefore, we would like to reinforce some of our previous suggestions: Inform learners about their need for instructional support and the value of the collaboration script, fade out structural support based on an on-line assessment of the quality of collaborative inquiry, and provide structural support via the interface of the learning environment.

7. Conclusions

We developed a prototype of a stoichiometry learning environment that included a collaboration script, a simulated chemistry laboratory called *VLab* (http://www.chemcollective.org/applets/vlab.php) and a cognitive tool, which provided note-taking and mind-mapping functionality. The prototype was computer-based with the exception of one structural component of the collaboration script, namely the sequence of inquiry activities, which was instructed on paper. The environment provided feedback to learners based on an on-line assessment of the quality of their collaboration and inquiry activities. In this paper, we reported an initial exploratory study in which we had pairs of students work on a stoichiometry problem using the learning environment, with half of the dyads being supported by the collaboration script and half of the dyads not receiving instructional support for collaborative inquiry learning. Our quantitative analyses consisted of comparisons of the learning outcomes and learning experiences under the two conditions. Using a qualitative approach, we also analyzed the learning processes of two dyads from the scripted collaboration condition. The qualitative analysis focused on the effects of script support on collaborative inquiry learning, the actual implementation of the collaboration script and learners' interactions with the computer-based learning environment. We drew a number of conclusions from the findings which yielded implications with regard to improvements of the collaboration script as well as the instructional design, interface design and interaction design of the learning environment. As our larger research program aims at a learning environment that integrates the various components and provides automated adaptive support for collaborative inquiry, these design implications will feed into another cycle of development and testing. In the following, we summarize our plans for improving the design of the stoichiometry learning environment. The summary moves from the overall design of the learning environment to more specific aspects.

7.1. *Designing for stoichiometry learning*

None of the components of the stoichiometry learning environment provided instructional support for interrelating the multiple representations of the virtual chemistry laboratory, although this is known to be a very challenging task for chemistry learners (Ainsworth, 2006; Gabel, 1998). In the next design cycle we will, therefore, develop and implement instructional support for relating representations. We plan to combine prompts for active connection-making with dynamic system features that support interrelating representations by automatically updating representations, thus highlighting relevant information. The focus of the connection-making will be on deep structural relations, rather than surface features.

A need for basic algebra skills training and instruction on general chemistry concepts emerged from our study. Therefore, the stoichiometry learning environment will be redesigned following the instructional design model of Van Merriënboer *et al.* (2002). More specifically, (1) the collaborative inquiry activities will be interspersed with practice items (e.g. transforming fractions) and (2) explanations of key chemistry concepts (e.g. endothermic/exothermic reactions) will be made available to the learners via the interface of the learning environment. Learners' attention will be directed to specific explanations depending on their prior knowledge in order to ensure high relevance of the information to their learning and, thus, increase the probability of deep cognitive processing.

7.2. *Designing for deep learning*

Despite being instructed to engage in conceptual reasoning by the collaboration script, the participants of our study tended to focus on carrying out procedures. Furthermore, shallow reasoning seemed to prevail. Thus, the collaboration script has to be improved to bring to bear the benefits of collaborative learning. We plan to redesign Phase 2 (Developing a strategy) and Phase 4 (Analyzing the experiments) of the collaboration script. Each of the two phases will be split in such a way that procedural activities follow conceptual activities. For example, learners will be instructed to interpret and discuss the results of their experiments based on raw values or very rough calculations before they move on to fill in equations and calculate exact solutions. In addition, monitoring will be facilitated by assigning an explanatory role to one of the learners and a metacognitive role to the other learner.

7.3. *Designing for productive collaborative inquiry*

The results of the two case studies suggest that learners may master some of the demands of collaborative inquiry without instructional support. But they tend to miss opportunities for learning from collaborative inquiry when they do not make use of the instructional support provided to them. We also saw that the perceived value of the collaboration script as a means of instructional support points toward necessary improvements. Therefore, the collaboration script will be developed further: (1) The next version of the collaboration script will see the paper-based structural support component, meaning the sequence of inquiry activities, implemented via the interface of the stoichiometry learning environment. That way we hope the structural support will not be perceived as extraneous material or an additional resource but a core feature of the learning environment. (2) Informed training on the sequence of inquiry activities will precede the learning phase. The training will include feedback on the learners' collaboration and inquiry skills. (3) Brief explanations of what triggered an adaptive prompt will be added to the pop-up messages. Students will be able to access these explanations at any time during the learning phase.

7.4. *Designing for different learner needs*

The two case studies also highlighted strengths of our approach to scripting: The low degree of coerciveness of the structural support components allowed the learners to adapt the collaboration script to their needs. And learners were given adaptive support (by the Wizard of Oz) only when the quality of their collaborative inquiry indicated a need for assistance. As our collaboration script seems a very promising approach we plan to turn the structural support components into adaptive support components in the next design cycles. For this to be accomplished, we first have to develop an assessment tool. The tool will be used to assess the learners' collaboration and inquiry skills at the outset of the learning phase. Then, the interface of the stoichiometry learning environment has to be redesigned to allow for adaptation. Alongside the development of the assessment tool and the adaptive interface, we will continue to develop the original adaptive support components. We will develop an assessment tool for evaluating the quality of collaborative inquiry. As automated adaptive support for stoichiometry learning is the ultimate goal of our research program design efforts will also be made in that direction. Furthermore, the practice items and explanations of key concepts (see Section 7.1) will also be macro-adapted to the collaborating learners' needs.

7.5. *Designing for productive learner-system interactions*

We pointed out difficulties associated with the use of the virtual chemistry laboratory to the participants during the preparation phase of our experiment. As seen in the first case study (Sio and Adi), the instructions were insufficient: The dyad did not switch between the aqueous species tab and the solid species tab although that would have been necessary to solve the stoichiometry problem. Hence, we strongly recommend to improve the interface design and interaction design of the virtual chemistry laboratory. In addition, we would like to make a plea for redesigning the simulation to provide for more authentic learning experiences. We do not elaborate on our recommendations in this paper as research on the design of the virtual chemistry laboratory has been reported elsewhere (e.g. Evans *et al.*, 2008).

Feasibility issues will certainly limit the number of planned developments that we will be able to realize in the upcoming design cycle. Yet, we believe that after just a few additional design cycles and test runs the learning environment can be used productively for collaborative inquiry and, hence, to improve stoichiometry learning.

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