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CoChemEx: Supporting Conceptual Chemistry Learning via Computer-Mediated Collaboration Scripts

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Abstract. Chemistry students, like students in other disciplines, often learn to solve problems by applying well-practiced procedures. Such an approach, however, may hinder conceptual understanding. We propose to promote conceptual learning by having pairs of students collaborate on problems in a virtual laboratory (VLab), assisted by a computer-mediated *collaboration script* that guides the students through the stages of scientific experimentation and *adapts* to their needs for support. We used the results from a small-scale study comparing how singles and dyads solve chemistry problems with the VLab with and without scripts to develop a scripted collaborative experimentation environment. A subsequent small-scale study compared an adaptive and a non-adaptive version of the system. Qualitative data analyses revealed a tendency for the dyads in the adaptive feedback condition to improve their collaboration and be more motivated than the non-adaptive dyads. In this paper, we present our research framework and report on preliminary results from the two small-scale studies.

1 Introduction

Chemistry educators face the challenge of teaching students to solve problems *conceptually* rather than simply applying mathematical equations, a common tactic taken by students. Students struggle with problems that are similar to those illustrated in a textbook or demonstrated in the classroom, because they do not grasp the similar underlying concepts [1]. Research in chemistry education has suggested that *collaborative* activities can improve conceptual learning [2, 3] and increase student performance and motivation [4]. While there have been very few controlled experiments investigating the benefits of collaborative learning in chemistry, evidence that collaboration is beneficial exists in other disciplines, such as physics [5] and scientific experimentation [6]. Our own experimental work has also shown promising preliminary results in the conceptual learning of algebra [7]. This evi dence has led us to investigate the potential advantages of collaborative activities for the acquisition of conceptual knowledge in chemistry.

Unfortunately, collaborative partners often do not engage in productive interactions and thus miss the opportunity to benefit from their collaboration. This observation, taken together with research in the area of collaborative inquiry learning [8] and scientific scaffolding [9], suggests supporting students with *collaboration scripts*. By scripting collaboration we mean providing prompts and scaffolds that guide students through their collaborative work (e.g., [10]). However, it is also possible to *over-script*, that is to provide too many scaffolds [11]. Students may be overwhelmed by the concurrent demands of collaborating, following script instructions, and trying to learn [12]. To avoid the pitfalls of over-scripting but at the same time provide collaborative scaffolds, we propose to use *adaptive scripting*, i.e. scripting that adapts to the collaborators' needs for support. We intend to enforce and/or fade support based on real-time, dynamic estimations of the student's domain and collaborative knowledge. We believe that students at different levels of knowledge and skills will be supported better via varying degrees of collaborative scaffolding. Some studies by other researchers have pointed toward the benefits of such adaptive support [13]. More particularly, we want to adapt the script, the system support in terms of tools provided to the students, and the prompts. We hypothesize that this approach will increase the likelihood that students will capitalize on the learning opportunities offered by the experimental chemistry environment.

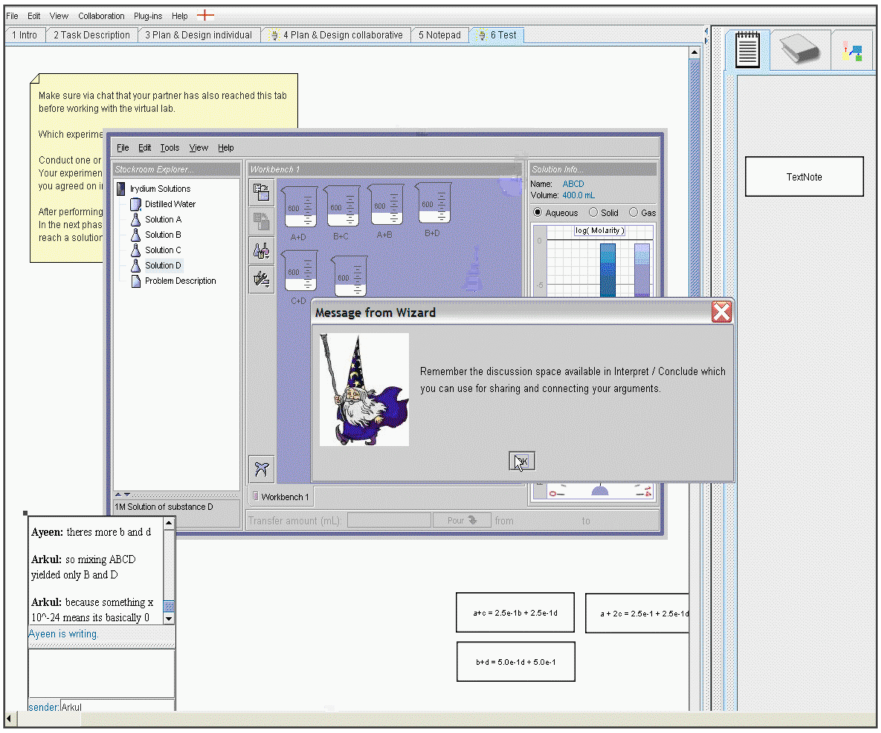
In the current paper, we describe the software we have developed, our pedagogical approach, the small-scale studies we have conducted so far together with a case analysis of adaptive human prompts and consequent student behavior, and our plan to extend our system to produce fully automatic adaptive feedback.

2 Technology Integration in the CoChemEx Project

We developed collaborative extensions to VLab, a web-based software tool that emulates a chemistry laboratory and supports chemistry experiments [14]. VLab was developed at Carnegie Mellon University. It provides virtual versions of many of the physical items found in a real chemistry laboratory, including chemical solutions, beakers, Bunsen burners, etc. It also includes meters and indicators for real-time feedback on substance characteristics, such as concentration and molarity. The idea behind the VLab is to provide the students with an "authentic" laboratory environment in which they can run experiments to solve chemistry problems much like in a real chemistry lab.

In order to allow students to collaborate during the simulation of chemistry experiments, we integrated the VLab into an existing collaborative software environment called FreeStyler [15], a collaborative software tool that is designed to support "conversations" and shared graphical modelling facilities between collaborative learners on different computers. Figure 1 illustrates the FreeStyler software and the VLab (in the middle). FreeStyler provides a variety of objects (top right in Figure 1), such as the *chat* shown in the lower left of the figure and a graphical *argument space*, which supports unfolding debates between users. All users have access to a shared workspace (essentially the entire window shown in Figure 1) that may be updated by any participant in the collaboration.

Fig. 1. A screenshot of the computer-based CoChemEx script, showing the *Test* tab (to be explained later)



FreeStyler also supports the implementation of inquiry and collaboration scripts which are formally represented as an IMS Learning Design document, an e-learning standard for educational processes. These scripts are enacted using a third-party component for the scripting engine, the CopperCore learning design engine. As explained in more depth in [15], the scripts can control the tools available within FreeStyler (e.g., *chat*, *argumentation space*, or VLab) for each phase of a learning activity: actions conducted by the learners in the learning tool are propagated to the scripting engine, analyzed, and the learning environment is subsequently reconfigured based on the information contained in the script. That way, adaptive system behavior is achieved. We complemented this system-initiated option of regulating the learning processes with a possibility of having a human supervising the collaboration and giving advice in a Wizard-of-Oz fashion. This Wizard Component allows the human observer to send text messages and pictorial information directly to an arbitrary set of collaborators (see Figure 1). The use of the “Scalable Adapter” design pattern [16] and the cost-effective re-use of existing software code made this development possible.

3 The General Pedagogical Approach

Our approach to scripting, which we have tested in the two small-scale studies described in the following section, is to guide the collaborating students through phases of scientific experimentation and problem solving. More specifically, we base our script on the kinds of cognitive processes identified as typically used by experts when solving scientific problems experimentally [17, 18]. For instance, de Jong and van Joolingen have identified Orientation (identification of main variables and relations), Hypothesis generation, Planning, Experimentation (changing variable values, predictions, interpreting outcomes), Monitoring (maintaining overview of inquiry process and developing knowledge), and Evaluation (reflecting on acquired knowledge) as steps that scientists do and should take in their work. Our experience with a first version of the script, which resembled this analysis of scientific steps a lot and asked students to follow them closely, led us to a necessary simplification. The main steps of the current script, illustrated at the top of Figure 1 as tabs, are: *Plan & Design*, where partners discuss their individual plans and agree on a common plan, *Test*, where the experimentation in VLab takes place, and *Interpret & Conclude*, for discussing the results in VLab and drawing conclusions. We also now guide students through the various steps in a less rigid manner to avoid overwhelming them with too much structure.

Our system gives students general guidance on the script and provides prompts on solving VLab problems collaboratively. This approach is similar to that of White *et al* [19] and Van Joolingen *et al* [20] which scaffold students who collaboratively solve scientific problems. However, our work differs to these prior efforts mainly in that we investigate how such an approach can be automated and if it can bolster specifically the collaborators' *conceptual knowledge* in the domain.

4 Studies and Script Development

4.1 Study 1

This was a preliminary study of the collaboration scripting approach described above. Data was collected on four conditions: scripted and unscripted dyads (4 dyads in each condition), scripted and unscripted singles (4 singles in each condition). The scripted conditions were given a paper-based script (without computer support) inspired by [17, 18]. It consisted of the steps *Orientation*, *Experimentation* (with substeps *Hypothesis*, *Design of Experiments*, and *Analysis*), *Drawing a Conclusion* and *Making an Evaluation*. The participants working in dyads sat next to each other and were asked to collaborate either freely, in the unscripted condition, or based on the script, in the scripted condition. They collaborated on solving problems that involved performing experiments in the VLab. The singles' problem-solving was supported by a similar script to test the effect of the script independent of the collaboration. The unscripted singles were the control; they solved the same tasks in the VLab with no further instructions. Students had to solve two problems: one on titration, and one on reaction stoichiometry and limiting reagents.

Perhaps unsurprisingly, the scripted conditions reported problems and frustration in dealing with the script in the overall complex situation. As mentioned earlier, previous work has shown that scripted dyads can be overloaded by the demand of getting acquainted with a computer-based learning environment, collaborating with a partner, attending to a script, and solving a task all simultaneously [12]. However, our results also indicated that, in spite of the perceived constraints of the script, it was still helpful. For instance, the scripted conditions were more efficient in solving problems; they took fewer steps to achieve similar results.

Improvement of the collaboration script based on study 1: The analysis of the first study led to three consequent adaptations of our script:

- First, we reduced the complexity of the script. More specifically, as mentioned above, we consolidated the experimental steps to three phases: *Plan & Design*, *Test*, and *Interpret & Conclude*.
- Second, we modified the script so that individual phases precede the collaborative ones, to allow students to formulate ideas first at their own pace, before entering the collaboration phases.
- Third, we added adaptive feedback to support students according to their individual needs in the different phases. This feedback is provided by a human "wizard"; later we intend to automate the production of adaptive feedback.

Figure 1 illustrates the resulting collaborative learning environment that we developed. Students are guided by static instructions in each tab. The first tab is the *Task Description*. The tabs *Plan & Design individual* and *Notepad* allow each of the participants to record private notes and ideas using free-form text, in preparation for collaborating. The tabs *Plan & Design collaborative*, *Test*, and *Interpret & Conclude* implement the script to guide the students' collaborative experimentation. Finally, in the tab *Check Solution* students submit their solutions and get error feedback. In the first cycle, the students are requested to follow this pre-specified order of the tabs and to click on a "done" button to activate the next tab. After the first cycle, all tabs are available for a more open exploration.

Collaborating students work on separate computers and have access to a number of tools. The *VLab* (in the middle of Figure 1) is the basic experimental tool and the core collaborative component; it is situated in the *Test* tab. The *chat* window in the lower left of Figure 1 supports free-form communication between the students in the *Test* tab, as a way to explain, ask/give help, and co-construct conceptual knowledge. An *argument space* is available in the tabs *Plan & Design collaborative* and *Interpret & Conclude* (Figure 1). It allows the collaborators to discuss their hypotheses and results and to communicate general ideas, so as to promote students' conceptual understanding of the experimental process. It provides students with different shapes and arrows of different semantics for connecting the shapes. By using them, students can make claims, provide supporting facts, and make counter-claims. In the shapes we provide sentence openers to guide the argumentation, such as "I think that the main difference between our approaches to the problem is..." The argument space has the potential to allow students to reflect on each other's ideas and understand them better [21]. Finally, a *glossary* of chemistry principles is available to the students at all times.

A human wizard provides adaptive support (see Table 3) using a flowchart to observe and recognize situations which require a prompt, and to choose the appropriate prompt. The situations are defined by observable problematic behaviors in the tab where the activity currently takes place, either with regard to the collaboration (*bad collaborative practice*, e.g. ignoring requests for explanations), or with regard to following the script (*bad script practice*, e.g. moving to the next tab without coordinating with the partner). The wizard prompts were focused on providing collaboration support. A top-down version of the flowchart of prompts was first developed by reviewing the literature on collaborative learning, for example [5, 22]. Moreover, we focused our adaptive feedback on prompting for communication (e.g., reminding to give and request explanations and justifications) and prompting after poor communication (e.g., reminding not to ignore requests for explanations or to contribute to the activities equally). This was a reaction to results from the small-scale study, which revealed that students did not exhibit the right amount and kind of communication. A few prompts specific to our script were added to the flowchart to remind students which tabs to use for their activities. Finally, domain-specific hints were added as a type of "dead end prevention" in case students submitted a wrong solution. Two wrong submissions were allowed; after that no more attempts were possible.

4.2 Study 2

In a second study our goal was to test our computer-based collaborative learning environment and to refine the scripting approach based on an in-depth analysis of the data, with a focus on the adaptive aspects of the script. We again planned a small study to get preliminary indications on whether an adaptive system would lead to conceptual learning gains. We recruited 3 dyads per condition. All participants were university students. The experimental process followed the standard pre-test – intervention – post-test paradigm. In the intervention phase, there were two conditions, one using the standard and one the adaptive version of the script. That is, the adaptive social prompts by the human wizard were unique to the adaptive condition. Both conditions had to solve two problems: one dealing with limiting reagents in Reaction Stoichiometry, and one dealing with molarity. Both problems were of average difficulty for the participants, with the latter being slightly more demanding. After the intervention phase a post-questionnaire and a post-test were administered. The post-test was equivalent to the pre-test, but included additional conceptual questions.

Quantitative Results The results showed a tendency toward better conceptual understanding in the adaptive condition. Two conceptual questions were asked in the post-test for each of the problems. The concepts tested were all central to the tasks which students had encountered in the VLab. With a highest possible score of 6 points, the mean of the adaptive condition was M=4.6 (SD 1.63) whereas the non-adaptive condition scored in average M=3.5 (SD 2.81). Due to the small sample size we did not perform further statistical analyses. An interesting result from the analysis of the questionnaire was that the adaptive condition reported on a 6-point Likert scale a stronger impression that they did not have an equal chance to participate in solving the problems (M_{ad}=5.16, SD_{ad}=1.16 vs. $M_{non\text{-}ad}$=2, $SD_{non\text{-}ada}$=.89), although our process analysis revealed that such a difference is not real. This could be a cue that the common wizard prompts to participate equally raised the participants' awareness of instances when participation was not equal. That is a desirable effect especially if it leads to corresponding attempts to balance participation.

Table 1. Summary of the process analysis of the script and collaboration practice.

Analysis Category	Number of Occurrences			
	Adaptive		Non-adaptive	
	M	SD	M	SD
Good script practice, e.g., coordinated actions in tab	6.33	2.51	5	2.64
Bad script practice, e.g., uncompleted actions	4.33	3.21	7.33	2.3
Good collaborative practice, e.g., ask for and give explanations	5.66	1.15	3	1
Bad collaborative practice, e.g., not explaining actions	2	1	1.66	1.15
Good reaction to a wizard message, e.g., improved practice after	8	4.58	(does not apply)	
Bad reaction to a wizard message, e.g., message has no apparent effect	6	4.7	(does not apply)	

Progress of individual dyads	***Ad-Dyad-1***: improved	***Ad-Dyad-2***: improved	***Ad-Dyad-3***: improved (slightly)	***Non-Ad-Dyad-1***: deteriorated	***Non-Ad-Dyad-2***: deteriorated (slightly)	***Non-Ad-Dyad-3***: stable

Process analysis of Study 2 Data The process analysis of the screen recordings of the collaborations revealed interesting differences between the two conditions, as shown in the summary in Table 1. Three members of our research team annotated different screen recordings independently. We counted the number of occurrences of good and bad *script* practice per dyad, that is, student's behavior relating to the script features (tab structure, argument space, and instructions). We also counted good and bad *collaborative* practice, that is, the kind of behavior expected and fostered by the prompts in the wizard's flowchart.

As shown in Table 1, there was a big difference between conditions and for both problem-solving sessions in the aggregated occurrences of "good script practice" and "good collaborative practice" in favor of the adaptive dyads. "Bad script practice" was also considerably less frequent in the adaptive condition. However, the adaptive dyads showed slightly worse collaborative practice than the non-adaptive dyads. The category "Progress of individual dyads," at the bottom of Table 1, is a qualitative overall evaluation of each dyad as perceived by the annotators. It is a summary of the script and collaboration practice and the reaction to the wizard messages in the adaptive condition, per dyad. Notice that the adaptive dyads all improved, while the non-adaptive dyads remained stable or deteriorated.

To further illustrate these descriptive differences, we present a detailed analysis of two dyads, one in the adaptive (*Ad-Dyad-1* in Table 2) and one in the non-adaptive condition (Non-*Ad-Dyad-1* in Table 3). We indicate situations in which the wizard gave a prompt to the adaptive dyad and similar situations in which our analysis showed that a prompt could have been useful in the non-adaptive dyad. We compare the resulting behavior of the two dyads and their overall behavior as it evolved during their interaction with the system. Tables 2 and 3 outline the two sessions; Table 3 additionally includes the interventions of the wizard in the form of prompts.

Table 2. Outline of the collaboration process of a non-adaptive dyad

Elapsed Time	Student Behavior
15:32	They collaborate well, follow the script and make a plan, e.g., "Can we react two chemicals at a time or will the reaction be different when we mix all three together?"—*"I don't think it is different with two than with four"*
21:23	One partner asks the other to explain what he is doing, e.g., "Did you just make OH and H or were they there? And where did it all go?"
27:44	Their hypothesis is not well formulated. They don't say what they expect to happen, e.g., im gna add more d until it's a decent number and see what happens…because it seems to be limiting"
56:54	They do not explain their interpretations and start making conceptual mistakes, e.g., "ok be is going to be 2 on the left side" – *"well d has to be larger than 2 right?"* – "cant we just mix a certain amount on the left until we get an even ratio as a product…"
1:00:08	Error message after submitting a solution: "Remember that a chemical reaction describes a transformation from one /some compound/s to another. Note that no compounds should appear in the same side of the equation. Please correct the equation and try again"
1:01:08	They try to understand the error message together and collaborate again, e.g., "makes more sense now…so b and c are on one side and a and d are on the other" – *"so the coefficients for B and c on the left are zero?"*
1:07:35	They are demotivated and give up on finding the solution, e.g., "we have no chance its your turn to guess"

Non-adaptive Dyad: This pair of students collaborated well at the start and seemed motivated to follow the script. However, there were a few significant flaws in their interaction. To start with, they didn't have a well-formulated hypothesis. As a consequence, they had trouble interpreting their results. Conclusions were left without explanation as to how they were supported, and they divided labor so that they actually reduced the amount of thinking they did together. Explanations and requests for explanations decreased over time. They didn't use the designated tabs for their designed activities. Towards the end of the intervention period, they appeared to be discouraged and were not seriously trying to solve the problems. Adaptive scripting aims at avoiding such behavior and providing encouragement through appropriate help. Given the positive disposition of the dyad to collaborate at the beginning of the interaction, it may have been useful for this dyad to receive prompts to plan collaboratively, follow the script, use the designated tabs and so on in the situations mentioned above. In fact, they responded well to the "dead end" prevention hint from the wizard (Table 2, 1:00:08) after submitting an incorrect initial solution, and reported to have liked it a lot. This hint also encouraged them to collaborate again, as they tried to understand it together (Table 2, 1:01:08).

Table 3. Outline of the collaboration process of an adaptive dyad

Time	Student Behavior	Wizard	Reaction
9:06	The two partners are in different tabs. One starts doing everything alone in VLab.	"Remember to build your argument on your partner's argument."	The other partner expresses that he is having trouble following, e.g., "We already got them up there?"
17:22	The "stronger" partner does not explain his actions		The "weaker" partner insists on working together, e.g., "What do we want to do? Make them all equal?"
24:27	They don't have a hypothesis and they just "play" within the VLab.	"Don't forget to share the experimentation in the virtual lab."	They start working together and it transpires that one of the students is lost, e.g., "Do you want to pour them?" -- *"Which ones?"*
29:54	They don't have a good plan for experimenting.	"Discussing which experiment best addresses the problem will help you in solving the problem. Remember the discussion space available in Plan/ Design and Interpret/ Conclude"	They don't move tabs, but they do discuss their results, e.g., "Looks like A and C are in the same rations. And D is 1/3 of A and C"
37:48	They have trouble interpreting the results of their experimentation.		The students who had the lead until now starts asking for feed-back and recapitulates the actions for both, e.g., "I feel like it's [what he is doing] right, but I'm not quite sure" -- *"That's OK. Sounds right"* – "So we mixed them all together. Started of with 50 ml of each"
46:29	They seem to have a problem with mols.	"The chemical terms most relevant to the problem are explained in the glossary."	They don't use the glossary, but the "stronger" student asks his partner for help in calculating mols.

Adaptive Dyad: In contrast to the non-adaptive dyad, this dyad started out badly with a lot of conceptual gaps and almost no collaboration. They did not make a plan or propose a hypothesis. The "stronger" student started doing everything alone without agreement. They played around aimlessly in the VLab, and resisted taking the prompts into account. After a number of prompts, the "weaker" student started asking questions to understand what was going on and insisted on working together. His partner started explaining shallowly at first, but progressing into deeper explanations, including a recapitulation to bring his partner up to speed. Interestingly, the "weaker" participant never contributed much in terms of content, but started encouraging his partner in a way that induced collaboration and motivated the dyad to reach the correct solution, despite a very long session.

This outline of the two contrasting dyads, while certainly anecdotal, illustrates how a good collaboration can gradually deteriorate due to a lack of adaptive guidance and on the other hand, how a collaboration that starts poorly can improve with support. Given periodic prompts at strategic times, the second dyad was led to an almost model collaboration and showed great motivation to complete the task, notwithstanding a bad attitude towards the prompts. The non-adaptive dyad was not able to correct flaws in their collaborative or script practice. On the contrary, the tendency in the adaptive dyads in general was to start out mostly ignoring the prompts by the wizard and gradually begin considering them, probably as they realized that they *did* need help. Although a lot of prompts were ignored or not followed to the letter (see, for instance, Table 3, 29:54 and 46:29), considering at least some of them had a clear effect on this dyad's collaboration practice.

5 Discussion and Outlook

We presented our research framework and reported on preliminary results from two small-scale studies. We described how the knowledge gained from the first study led to a refined version of our collaboration script and the development of a collaborative computer-based environment. In the second small-scale study we collected data on an adaptive and a non-adaptive version of the script. We believe that our process analysis provides solid initial directions for the future development of the collaborative platform.

In terms of improvements to the script, we plan to keep its general structure,but make movements between tabs more flexible. Currently, the tabs are fixed to specific script phases. Yet, in our small-scale studies, we observed students' need to move back and forth between tabs to consult the content of previous work phases (e.g., notes taken). This practical need often prevented them from using the tabs as the script recommend. Also most of the prompts which were ignored were the ones that insisted on the use of the tabs in the prescribed sequence, which is another indication that this aspect needs to be changed.

Following such observations, Isabel Braun and Nikol Rummel conducted a study in Germany, where German students collaborated on solving a problem in a German translation of the VLab. In this study, dyads of students sat side-by-side in front of one computer, both having their own keyboard and mouse. A scripted collaboration condition was compared to an unscripted one. The script was, however, not implemented as part of the computer-supported environment, but was administered to participants in the form of a small booklet. Each phase of the inquiry cycle was presented on one page of the booklet (instead of the tabs). Students were instructed to work through the phases one by one but the sequence was not enforced through system restrictions. Instead, fidelity to the script was prompted only when students did not engage in the most important activities of each phase. Thus, learners in this study were freer to move around phases, as they felt appropriate. Also the paper-based version of the script made it easier for the learners to switch between phases. The *argument space* and the VLab were visible on separate computer screens, thus allowing students to look at the script (booklet), their notes and the VLab simultaneously. Data analysis is currently underway. We hope to gain further insights from this lower-tech study as to whether the proposed changes to our computer-based environment go into the right direction, and whether the strengths and weaknesses of our system lie on the implementation of the script in the environment or on its conceptualisation. According to Dillenbourg and Tchounikine [23], the first pertains to *extrinsic constraints* and would require changes in the system, whereas the second might pertain to *intrinsic constraints*, which would require changes in the pedagogical setting of the script.

We also plan to automate the feedback provided by the system based on the specific student actions of and the system knowledge about the collaborators. For the *Test* tab in particular, we will explore action analysis (e.g. [24]). We will extend Mühlenbrock's approach by analyzing the student actions in the VLab with machine learning techniques to identify situations in which prompts are necessary. To this end we will use the collaboration expertise in our group, which is already captured in the wizard flowchart in terms of feedback for particular situations, and we will improve it according to the new data.

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