Extending a virtual chemistry laboratory with a collaboration script to promote conceptual learning

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Abstract: We developed collaborative extensions to 'Vlab', a web-based laboratory that supports students in conducting virtual chemistry experiments. While results from a recent study indicated that VLab promotes chemistry learning, they also revealed that there is room for improvement. We embedded VLab into a collaborative environment that implements a computer-supported *collaboration script* for guiding students through the stages of scientific experimentation. We describe our pedagogical approach, our collaboration script, and the collaborative learning environment which implements it. We present results from two small-scale studies and a contrasting-case analysis of how adaptive prompts, in addition to the fixed script, affected student behaviour.

Keywords: computer-mediated collaboration; collaboration scripts; adaptive scripting; scaffolding; conceptual learning; experimentation phases; inquiry learning; chemistry education; virtual chemistry laboratory; automatic feedback.

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1 Introduction

We have developed collaborative extensions to 'Vlab', a web-based software tool that emulates a chemistry laboratory and supports chemistry experiments (Yaron et al., 2003). The idea behind the VLab is to provide students with an 'authentic' laboratory environment in which they can run experiments to solve chemistry problems, much like in a real chemistry lab. A recent classroom study demonstrated the effectiveness of VLab: a significant positive correlation was found between the length of interaction with the tool and post-test scores (Evans et al., 2008). Nevertheless, the average post-test score was only 69%, indicating that there is still room for improvement. Such an improvement might be to set the VLab in a pedagogical context which takes better advantage of its educational value. We are suggesting such a context in this paper: we are proposing to embed the VLab into a collaborative environment and to support students' collaborative experimentation in the VLab by a computer-mediated script.

Research in chemistry education has suggested that collaborative activities can improve learning (Fasching and Erickson, 1985; Kozma, 2000) and increase student performance and motivation (Sumfleth et al., 2004). To date, there have been very few controlled experiments investigating the benefits of collaborative learning in chemistry.

However, evidence on the benefits of collaboration exists in other disciplines, such as physics (Hausmann et al., 2004) and scientific experimentation (Saab et al., 2005). Our own experimental work has also shown promising preliminary results in the conceptual learning of algebra (Diziol et al., 2007). Guided by this evidence, we are investigating the potential advantages of collaborative activities for the acquisition of conceptual knowledge in chemistry and, in particular, while experimenting with VLab.

Unfortunately, collaborative partners often do not engage in productive interactions and thus miss the opportunity to benefit from their collaboration (Dillenbourg et al., 1995). This observation, taken together with research in the area of scientific scaffolding (Quintana et al., 2004), suggests supporting students with *collaboration scripts*. By scripting collaboration we mean providing prompts and scaffolds that guide students through their collaborative work with the aim to trigger cognitive, metacognitive and social processes beneficial for learning (e.g., Kollar et al., 2006). However, it is also possible to *over-script*, that is to provide too many scaffolds (Dillenbourg, 2002). Conversely, weaker students may be overwhelmed by the concurrent demands of collaborating, following script instructions, and trying to learn (Rummel et al., 2009). To avoid the pitfalls of over- or under-scripting but at the same time providing collaborative scaffolds, we propose the use of *adaptive scripts*, i.e., scripts that adapt to the collaborators' needs for support during use of the collaborative VLab.

Against the background of the literature on inquiry learning and, in particular, collaborative inquiry learning (e.g., van Joolingen et al., 2005), our approach to scripting 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 which characterise the scientific experimentation of experts (De Jong and van Joolingen, 1998; Klahr and Dunbar, 1988). 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 script consolidates these phases into the following script steps: *Plan & Design*, where partners discuss their individual ideas for a plan and agree on a common plan, *Test*, where the experimentation in VLab takes place, and *Interpret & Conclude*, for discussing and interpreting the results in VLab and drawing conclusions.

In addition, our current system scaffolds students by providing them general guidance on collaboration and on solving VLab problems collaboratively. This approach is similar to those of White et al. (1999) and van Joolingen et al. (2005) which scaffold students who collaboratively solve scientific problems. However, our work extends these prior efforts in that we investigate to what extent the approach can be automated. Ultimately, we aim to use adaptive scripting 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 with varying degrees of collaborative scaffolding. In this respect, our work overlaps with the recent research by Gweon et al. (2006) and Kumar et al. (2007) on adaptive support for collaborative learning. For instance, Kumar and colleagues tested the effect of adaptive help in a collaborative setting of students working on Thermodynamics problems. A significant effect was found for collaboration and for scripting between a dynamic script condition and a no script condition. While their work focuses on manipulating the dialogue interaction between the collaborators, we concentrate on providing adaptive prompts for better collaborative behaviour and script practice.

In our current system, adaptive support is implemented by means of a human 'wizard'; that is, a confederate of the experimenter who is responsible for selecting the appropriate feedback to post from a set of predefined prompts. A flowchart which defines interaction situations requiring feedback helps the wizard to decide which prompt to deliver. An alternative to our wizard messages is the approach taken by Vizcaino and du Boulay (2002) in the context of teaching programming. They had a simulated student posting messages to the chat that served the communication among the human collaborators. Moreover, our setting involves performing experiments in Stoichiometry and adds another factor to the collaboration, which we script based on experimental phases as the background of all other interactions.

We hypothesise that our overall approach to scripting collaboration will increase the likelihood that students capitalise on the learning opportunities offered by the experimental chemistry environment, VLab. Indeed, the results we obtained so far from two small-scale studies, although only indicative, revealed a tendency of the scripted conditions to perform more efficient experiments in the VLab, and a better conceptual understanding for the participants who received adaptive feedback. Moreover, our process analysis of contrasting cases suggests that the latter students followed the recommended script and improved the way they collaborated, as opposed to the students who did not receive adaptive help.

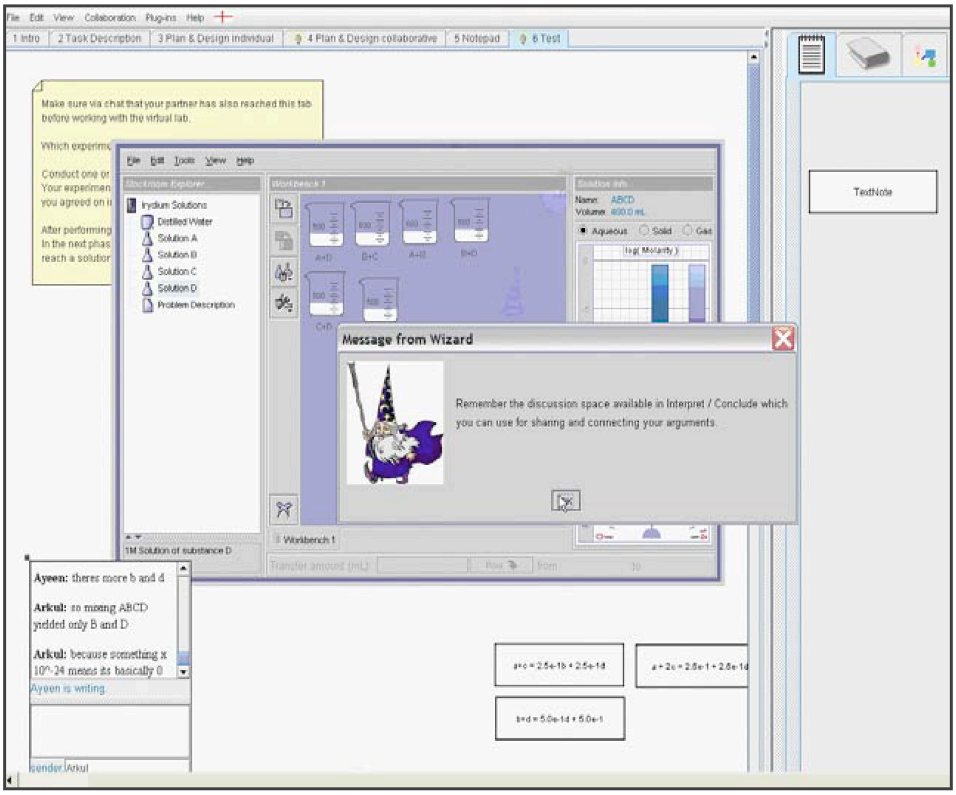
2 Collaborative extension of VLab

VLab was developed at Carnegie Mellon University. It allows students to solve realistic chemistry problems and apply their chemistry knowledge by planning and conducting experiments, and observing and interpreting the reactions. VLab provides virtual versions of many of the physical items found in a real chemistry laboratory, including chemical solutions, beakers, Bunsen burners, etc. The student can drag and drop substances and tools from a menu, which may be precompiled for specific problems, to a 'workspace' and perform actions like mixing, heating, weighing etc. To assist students, VLab also includes metres and indicators for real-time feedback on substance characteristics, such as concentration and molarity.

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 (Harrer et al., 2005; Hoppe and Gaßner, 2002) by making use of the 'Scalable Adapter' design pattern (Harrer et al., 2008). FreeStyler is a collaborative software tool for supporting concept mapping and graphical modelling between collaborative learners on networked computers. Figure 1 shows the user interface of FreeStyler with the VLab embedded in the middle. FreeStyler offers a variety of elements to the users, such as a *chat* (lower left of the figure) and a graphical *argument space* that allows users to visually represent debates and arguments. All participants in a collaboration session can manipulate a joint workspace (essentially the entire window shown in Figure 1).

In recent system versions, FreeStyler can also be configured with inquiry and collaboration scripts (formally represented as IMS Learning Design documents, an e-learning standard for educational processes). These inquiry and collaboration scripts are executed using the CopperCore learning design engine. As explained in more depth in Harrer et al. (2005), the scripts (controlled by CopperCore) can configure the tools available within FreeStyler (e.g., *chat*, *argumentation space*, or VLab) for each phase of a learning sequence: actions conducted by the learners in FreeStyler are transmitted to CopperCore, analysed there, and FreeStyler is subsequently reconfigured based on the information contained in the script. In this way, adaptive system behaviour is achieved. As we will describe in more details below, we complemented this system-initiated option of regulating the learning processes with a human supervising the collaboration and giving advice in a Wizard-of-Oz fashion (Dahlbäck et al., 1993). This Wizard component allows the human observer to guide and scaffold collaboration and learning by directly sending text messages and pictorial information to an arbitrary set of collaborators (see Figure 1).

Figure 1 A screenshot of the computer-based CoChemEx script, showing the *Test* tab (to be explained later) (see online version for colours)



3 Collaboration script

As introduced above, the script support in our collaborative learning environment comprises two components: phases of scientific experimentation consolidated into four script steps, and adaptive prompting on collaborative behaviours and on solving the VLab problems. Figure 1 shows the collaborative learning environment that we developed and illustrates both components of our script.

The script steps are represented by tabs at the top of the screen (note that not all tabs are shown in Figure 1). 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. Students are additionally guided by instructions in each tab. 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.

In our script model, collaborating students work on separate computers and collaborate synchronously. They have access to a number of tools in the different tabs. The *VLab* (in the middle of Figure 1), which is the basic experimental tool and the core collaborative component, 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). This 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 this tool, students can make claims, provide supporting facts, and make counter-claims. The shapes 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 bears the potential to allow students to reflect on each other's ideas and understand them better (de Groot et al., 2007). Finally, a *glossary* of chemistry principles is available to the students at all times.

An advantage of this kind of computer-mediated setup is that is allows for simultaneous, co-temporal action of the participants, but still enables them to review their communication and actions and – to some extent – revise them (Clark and Brennan, 1991). Moreover, the long completion times of real-lab experiments often cause students to lose track of the overall experimental process, whereas one of the affordances of virtual labs like the VLab are the reduced completion times (Bell, 2004). Using an asynchronous setting would again increase completion times and be counter to this technological affordance. Therefore, we opt for synchronous collaboration.

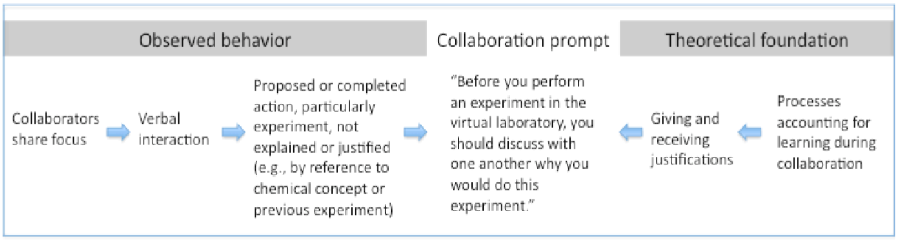
As described above, a human wizard provides adaptive support to promote positive collaborative behaviours during the experimental steps via prompts to the students. The wizard observes the students' collaboration on a separate computer far from the students to avoid a potentially intrusive physical presence and the students do not even suspect that the wizard is, in fact, a human being and a confederate of the experimenter. As far as the students are concerned, the help comes from an automated support system. An example of a wizard prompt promoting explanation would be "Remember to build your argument on your partner's argument". More examples of prompts are provided later in the paper, in Table 3. The wizard uses a flowchart (see Figure 2) to observe and recognise situations that require a prompt and to choose the appropriate prompt. The flowchart we employed was focused on collaborative, rather than domain-related aspects of the problem solving process. A review of the literature on collaborative learning (for example, Hausmann et al., 2004; Weinberger et al., 2007) led to a first top-down version of the flowchart of adaptive prompts. The flowchart identifies good and bad collaborative practice, such as

1 giving explanations and justifications vs. ignoring requests for explanations or building superficial consensus without deep understanding and failure to co-construct knowledge

2 motivated sequencing of learning activities, e.g., following a 'script', vs. negligence to coordination activities

3 equal vs. unequal participation.

Figure 2 An example of a collaboration prompt, which is pedagogically and empirically motivated (see online version for colours)



Source: Braun (2008)

The taxonomy was further refined in a bottom-up manner according to the data from a pilot study, which revealed that students either had not communicated enough or lacked the kind of communication that would likely result in co-construction of knowledge and deep understanding. Therefore, we decided to focus our adaptive feedback on prompting for certain collaborative behaviours (e.g., reminding partners to give and request explanations and justifications) and prompting after poor collaborative practices (e.g., reminding partners not to ignore requests for explanations or to contribute to the activities equally). A few prompts specific to our script were also added to prevent *bad script practice* and to remind students to use the right tabs for their activities, e.g., the *Interpret & Conclude* tab for interpreting the results of experimenting in the VLab. Finally, domain-specific hints were added to the flowchart as a type of "dead-end prevention" in case students submitted a wrong solution in the *Check Solution* tab. Two incorrect submissions were allowed; after the third incorrect submission no more attempts were possible and the correct solution was given away.

In effect, the situations included in the wizard flowchart are defined by observable problematic behaviours in the tab where the activity currently takes place, either with regard to the collaboration (*bad collaborative practice)*, or with regard to following the script (*bad script practice)*. Moreover, the wizard might post a prompt and insist that collaborators attend to a particular script step (=tab) or use a particular tool within a given tab, according to the overall progress of the collaborators. Consequently, we adapt three aspects of the script all based on the real-time assessment of the ongoing interaction: prompts are adaptively posted to the collaborators, emphasis on particular script steps is shifted, and the collaborators are urged to use specific tools from the ones provided. While, currently, the adaptive feedback is provided by the human wizard, we intend to automate the production of adaptive feedback in our next circle of system developments.

4 Empirical studies

This section describes two small-scale empirical studies that we conducted in order to inform our script and system development.

4.1 Study 1

The first study was a preliminary study of the collaboration scripting approach and a low-tech version of the resulting collaborative learning environment described above. Its aim was exactly to collect data for the final development of our script and environment. Data were 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 De Jong and van Joolingen (1998) and Klahr and Dunbar (1988). 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 worked on one computer, since our collaborative system had not been developed yet, 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 (the Oracle problem), and one on reaction stoichiometry and limiting reagents (the DNA problem).

Most of the participants (and dyads) completed the study in 2–3 h, with an average problem-solving time of 20 min for the DNA problem, and 37 min for the Oracle problem. The average problem-solving time and the number of problems solved by condition are shown in Table 1.

Table 1 Problem-solving times and numbers of problems solved by condition

Condition	*N*	*Avg. time DNA in min*	*Avg. time oracle in min*	*Solved DNA*	*Solved oracle*
Scripted dyads	4	19	43	3	2
Scripted singles	4	20	39	3	1
Unscripted dyads	4	18	27	4	3*
Unscripted singles	4	21	36	2	2

*In one session we had technical problems; the fourth dyad would probably also have solved this problem.

Due to the small sample size we did not analyse the data statistically. Descriptively, there is some evidence that both collaboration and scripting made a positive difference. With respect to collaboration, notice, from Table 1, that the collaborative conditions solved more problems than the singles conditions: the dyads solved 12 problems (7 DNA, 5 Oracle) while the singles solved only 8 problems (5 DNA, 3 Oracle). This effect cannot be explained as a time effect: the dyads used less time for their problem solving (18.5 min DNA, 35 min Oracle) than the singles (20.5 min DNA, 37.5 min Oracle) (see Table 1). However, clearly the numbers are so small that we cannot make any inferences from this.

In a questionnaire filled out at the end of the study, the scripted conditions reported on 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 demands of getting acquainted with a computer-based learning environment, collaborating with a partner, attending to a script, and solving a task simultaneously (Rummel et al., 2009). Perhaps it was the combination of collaborating with a partner, following the script, and using the VLab on the computer that caused the frustration and possible overload for the scripted dyads. The scripted singles, in contrast, had only two of these problem-solving aids to work with (i.e., the script and the VLab) and reported greater satisfaction with the scripts: 2 out of 4 self-reported that the script was helpful, e.g., "It challenged me to consider my own thought process and because of that I think I was able to solve the second problem faster".

Furthermore, we analysed the VLab logs, calculating how many times each VLab action (e.g., add flask, mix solution, move object) was taken, on average, in each condition. The results show that the scripted conditions, both singles and dyads, performed far fewer 'mix solution' actions (singles = 64.1; dyads = 75.5) than the unscripted conditions (singles = 151.1; dyads = 238.3) in solving both the Oracle and DNA problems. Fewer 'mix solution' actions is a measure of efficiency; it means that the participants in the scripted conditions took fewer steps to achieve similar results. This result could indicate that even though students did not think the script was helpful, it actually did improve their experimentation: by following the script, students might have designed their experiments according to their hypotheses, rather than pursuing a trial and error strategy. Contrary to the study by Evans et al. (2008), this effect can not be attributed to the VLab alone in this case since all experimental conditions used the VLab.

The analysis of the first study led us to adjust three script aspects whose final modified version we already discussed in Section 2. First, we reduced the complexity of the script. As mentioned above, we consolidated the experimental phases to three steps: *Plan & Design*, *Test*, and *Interpret & Conclude*. Second, we added individual phases which precede the collaborative ones. Students can now formulate their ideas first at their own pace, and they can then present in the subsequent collaborative phases. Third, we added the adaptive wizard feedback to address the students' individual needs in the different phases. We used the resulting enhanced version of our script to implement the computer-based collaborative learning environment which we used to conduct a second study.

4.2 Study 2

With the second study we aimed to test our enhanced computer-based collaborative learning environment and to further refine the scripting approach, emphasising the adaptive aspects of the script. Consequently, 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. 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 (the Oracle problem), and one dealing with molarity (the Jello problem). We did not use the DNA problem as in Study 1, because it proved too easy. Both of the new problems were of average difficulty for the participants, with the latter being slightly more demanding. To be able to analyse the interactions in-depth and refine our script, we collected video recordings of the computer screens during intervention, which show the actions taken in the environment, the posted prompts and the reaction of the students to them. 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.

Results: As with Study 1, we did not perform statistical analyses due to the small sample size. Nonetheless, the descriptive results from the two conceptual questions asked in the post-test for each of the problems indicate a tendency of the adaptive condition for better conceptual understanding. The concepts included in the conceptual questions were central to the tasks which students where asked to perform in the VLab. The highest possible total score was 6 points. The adaptive condition scored, on average, $M = 4.6$ (SD 1.63) and outperformed the non-adaptive condition, which scored $M = 3.5$ (SD 2.81).

There were some further descriptive differences between the two conditions in the post-questionnaire, which at least suggest that we are taking a good direction with the development of the adaptive system and prompts. On a 6-point Likert scale (1 = not at all – 6 = completely), students in the adaptive condition indicated that they enjoyed working with the learning environment more than those in the non-adaptive condition ($M_{\mathrm{ad}} = 3.3$, $\mathrm{SD}_{\mathrm{ad}} = 0.26$ vs. $M_{\text{non-ad}} = 2.6$, $\mathrm{SD}_{\text{non-ad}} = 0.26$) and that they would like to work more often with the system more than those in the non-adaptive condition ($M_{\mathrm{ad}} = 3$, $\mathrm{SD}_{\mathrm{ad}} = 0$ vs. $M_{\text{non-ad}} = 2.3$, $\mathrm{SD}_{\text{non-ad}} = 2.6$). The adaptive condition also assessed higher, both their chemistry knowledge ($M_{\mathrm{ad}} = 3$, $\mathrm{SD}_{\mathrm{ad}} = 0$ vs. $M_{\text{non-ad}} = 2.3$, $\mathrm{SD}_{\text{non-ad}} = 0.26$) and their Stoichiometry knowledge ($M_{\mathrm{ad}} = 3.3$, $\mathrm{SD}_{\mathrm{ad}} = 0.26$ vs. $M_{\text{non-ad}} = 2.6$, $\mathrm{SD}_{\text{non-ad}} = 0.26$) than the non-adaptive condition on a 5-point scale (1 = very weak – 5=very strong). These self-report results together are a good indication that students liked the adaptive script better and felt that they learned more by using it. This, in turn, can result in a desirable motivational boost.

Another intriguing outcome from the questionnaires was that students in the adaptive condition felt more strongly that they did not have an equal chance to participate in the tasks ($M_{ad} = 5.16$, $SD_{ad} = 1.16$ vs. $M_{non\text{-}ad} = 2$, $SD_{non\text{-}ad} = 0.89$), which was reported on a 6-point Likert scale (1 = not at all – 6 = completely). Still, we could not verify this through our process analysis. A possible interpretation of this discrepancy might be that the wizard prompts to participate made the participants of the adaptive condition more aware of any unequal participation. This effect can lead to improved collaboration, provided that the affected participants will strive to participate more.

Process analysis of study. In this section, we report on the process analysis of the screen recordings and discuss our interpretation of it. For our analysis, we counted the number of occurrences of good and bad script practice per dyad, which was operationalised as student behaviour relating to the features of the script (tab structure, argument space, and instructions). We also counted good and bad collaborative practice, defined as the kind of behaviour which the wizard prompts urged. Three members of our research team annotated different screen recordings independently.

We first look at a close contrasting account of two dyads: one from the adaptive condition and one from the non-adaptive condition. We look into similar situations which arose in the interaction of both dyads. We compare the effect that the wizard prompts had on the interaction of the adaptive dyad with the progress of the interaction of the non-adaptive dyad, which did not receive such adaptive prompts. We also evaluate the overall behaviour of the two dyads throughout their interaction with the system. Tables 2 and 3 sketch the two sessions, and Table 3 also shows the wizard's interventions through adaptive prompts.

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

Elapsed time	*Student behaviour*
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 do not 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 do not say what they expect to happen, e.g., im gna [I'm gonna] 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"

Table 3 Outline of the collaboration process of an adaptive dyad

Time	*Student behaviour*	*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 do not have a hypothesis and they just 'play' within the VLab.	"Do not 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 do not 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 do not 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 do not use the glossary, but the "stronger" student asks his partner for help in calculating mols

Non-adaptive dyad. *This dyad started out* collaborating well and seemed motivated, on the whole, to follow the script (Table 2, 15:32, 21:23). When taking a closer look, though, it becomes clear that their interaction suffered from significant flaws. They did not have a well-formulated hypothesis (Table 2, 27:44), which, in turn, hindered the interpretation of their results from experimenting in VLab (Table 2, 56:54). They stated conclusions without supporting them, and they divided labour so that they actually reduced the amount of thinking they did together and hence the possibility of co-constructing knowledge. Even the few explanations which they did provide at the beginning of the session progressively decreased. They also did not use the tabs for their activities as designated by the script. By the end of the session, they appeared to be discouraged and lost interest into solving the problems expressed also in their argument that even if they did not solve it they were "… still getting paid."

In our general approach, we chose adaptive scripting as a means to discourage such behaviour and to provide appropriate help to motivate students in their attempts. We observed a similar effect in the interaction of the non-adaptive dyad when the wizard gave them a "dead-end prevention" hint (Table 2, 1:00:08) as feedback to an incorrect solution they submitted. They reported that they liked that hint a lot and it indeed seemed to encourage them to collaborate again: they tried to understand it together (Table 2, 1:01:08). Given this positive disposition of the dyad to the hint and to collaborate at the beginning of their session, one can hypothesise that had they received the wizard prompts, for example, to plan collaboratively, follow the script, and use the designated tabs in the situations mentioned above, they would have had a good chance of improving their interaction.

Adaptive dyad. In contrast to the non-adaptive dyad, this dyad had a lot of conceptual gaps at the beginning and almost did not collaborate at all. This resulted in a prompt from the wizard to consider each other's arguments (Table 3, 9:06). They also did not try to form a common plan or hypothesis. They played around in the VLab and suggested actions without planning, which were characterised by concluding their weak suggestions with phrases like "… and see what comes out of it". The peak of their non-collaborative behaviour was that the 'stronger' student started working completely alone (Table 3, 17:22). They also tended to ignore the wizard prompts. However, after a number of prompts, the 'weaker' student started asking questions to understand what was going on and insisted on working together (Table 3, 17:22). His partner started explaining reluctantly at first (Table 3, 29:54), but did provide deeper explanations with time, culminating in a recapitulation to help his partner catch up (Table 3, 37:48). It is worth pointing out that the 'weaker' participant never contributed much in terms of content. However, he encouraged his partner in a way that induced collaboration and motivated the dyad to reach the correct solution, despite a very long session (Table 3, 37:48 and 46:29).

This outline of the two contrasting dyads illustrates how a good collaboration can gradually deteriorate for lack of adaptive support, and on the other hand, how problematic collaboration can improve with appropriate adaptive scripting. With the help of the prompts at strategic times, the adaptive dyad was led to an almost model collaboration and showed great motivation to complete the task, notwithstanding a bad attitude towards the prompts. Moreover, the flaws in the collaboration and script practice of the non-adaptive dyad remained unchanged, while the tendency in the adaptive dyads in general was to start out mostly ignoring the prompts by the wizard and gradually begin considering them. This can additionally be considered as an indication that the prompts were perceived as helpful. Although a lot of prompts were ignored and most were not followed to the letter (see, for instance, Table 3, 29:54 and 46:29), the once that were taken into account had a clear effect on this dyad's collaboration practice.

To generalise our observations from the contrasting account, we present a summary of the most important results of all six dyads which participated in the study in Table 4. The dyads which we reviewed more closely in Tables 2 and 3 appear in Table 4 as *Non-Ad-Dyad-1* (non-adaptive) and *Ad-Dyad-1* (adaptive) respectively. The analysis of the independent annotations revealed differences between the two conditions as a whole which support the case analysis which we just presented. Table 4 summarises the most important differences in the interactions on both tasks that the students performed in VLab. The sum of occurrences of "good script practice" and "good collaborative practice" was very different and favoured the adaptive condition. "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 in the summative analysis. The category "Progress of individual dyads", at the bottom of Table 4, is a qualitative overall evaluation of each dyad, as perceived by the annotators, from the beginning to the end of the session. It is a summary of the script and collaboration practice and the reaction to the wizard messages in the adaptive condition, per dyad. Strikingly, the interaction of all adaptive dyads improved, whereas the interaction of the non-adaptive dyads either remained stable or deteriorated.

Table 4 Summary of the process analysis of the script and collaboration practice

	Number of occurrences			
	Adaptive		*Non-adaptive*	
Analysis category	*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

5 Discussion and outlook

We presented our research framework for enhancing the VLab's pedagogical value by turning it into a collaborative experimentation tool and by scripting the students' activities in it. We also reported on descriptive results from two small-scale studies. We detailed how the knowledge gained from the first study led to a refined version of our collaboration script and our development of a collaborative computer-based environment. In the second study we collected data on an adaptive and a non-adaptive version of the script. Our process analysis of this data provided solid initial directions for the future development of the collaborative platform.

First, to improve the script that guides the experimentation in VLab, we plan to keep its general structure but make movements between tabs more flexible. Currently, the tabs are fixed to specific script phases. In our studies, however, we observed that students needed to move back and forth between tabs and consult the content of their work in previous phases (e.g., notes taken). This practical need often prevented them from using the tabs as the script recommended. Another indication that more flexibility of navigation is needed is that most of the prompts that were ignored by students were ones that insisted that students use the tabs in the prescribed sequence.

Isabel Braun and Nikol Rummel (Braun, 2008) conducted a study in Germany as a follow-up to these observations. In this study, German students collaborated on solving VLab problems in German. Students sat side-by-side in front of a computer to work in dyads, but they each had 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 are in the right direction, and whether the strengths and weaknesses of our system lie in the implementation of the script in the environment or in its conceptualisation. According to Dillenbourg and Tchounikine (2007), the first would pertain 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.

An adjustment to the intrinsic constraints of the script that we are considering is based on Kapur's (2008) work, which indicates that unstructured collaboration, followed by more structured collaboration, can lead to higher learning effects. Taking these findings into account, we want to test whether it is beneficial to let students first experiment freely in the VLab in an unstructured way before having them apply the script with the experimentation phases. This is indeed the pattern observed in our exposition of the adaptive dyad in Section 4.2, and it was also suggested by two bioinformatics students who helped test the system. Such a script design may, in turn, decrease the need to move back and forth during the structured scripting phases, as students might develop a basic understanding of the task during the unstructured phase. Arguably, too much moving back to previous tabs defeats the purpose of the structured script (i.e., the learning of the typical activity sequences in scientific experimentation).

We also plan to automate the system feedback based on specific student actions of, and the system's knowledge about, the collaborators. Providing such adaptive script support allows to gradually shift the control of the learning process from the system to the learners and thus supports increasingly autonomous and self-regulated collaboration and learning. To this end we will use the collaboration expertise in our group which was already captured in the wizard flowchart in terms of feedback for particular situations. We will improve this feedback according to the new data, by increasing feedback instances from which the students seemed to benefit more and by modifying the content and occurrence points of less helpful feedback. Running an experiment were the students evaluate the prompts on-the-fly might be another idea of gaining at least subjective feedback on how useful the students consider them to be, which may influence the students motivation to attend to the prompts. To automate the domain-specific feedback required in the *Test* tab, we are exploring action analysis (e.g., Mühlenbrock, 2004). We will extend Mühlenbrock's approach and analyse the student actions in the VLab with machine learning techniques to learn and identify situations in which prompts are necessary. Although, the particular adaptive prompts will be specific to stoichiometry, part of our goal is to contribute a generic approach, architecture, and mechanism to support the development of adaptive feedback in collaborative settings and scientific experimentation as a whole.

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