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Design of Interactive Protocols that Help Students to Prepare for Laboratory Work

Sjors Verstege, Wander Lamot, Jean-Paul Vincken, and Julia Diederen*

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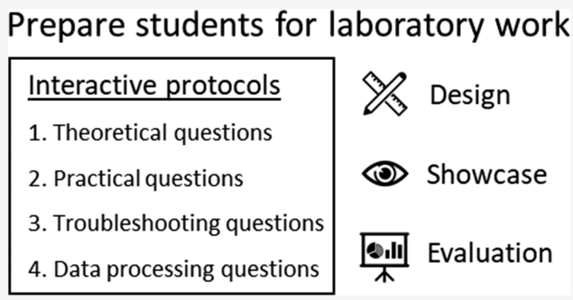
ABSTRACT: Laboratory education makes up an extensive part of natural science education at universities. To support meaningful learning during laboratory work, students should prepare by carefully studying the protocols. The aim of this study was to design and evaluate a preparative learning material that focuses on protocol steps with the design goal to help students to (i) understand the "why" (reason or theory) of protocol steps, (ii) make practical choices, and (iii) do troubleshooting. To reach this goal, protocol steps have been enriched with theoretical, practical, troubleshooting, and/or calculation questions to form interactive protocols. This design process resulted in a list of design choices (i.e., when to include a question and how to design a question) and a showcase of questions in the interactive protocols. These interactive protocols were implemented and evaluated in a real educational setting. From the evaluation results, it was concluded that the interactive protocols were successful in preparing students for the laboratory work. After the laboratory work, students reported a more diverse and slightly less positive contribution of the interactive protocols to their understanding of the protocol steps and their ability to make practical choices. A significant difference was found in the perceived usefulness of the troubleshooting questions before versus after the laboratory work, which is suggested as a topic for further investigation.



KEYWORDS: *Second-Year Undergraduate, Laboratory Instruction, Computer-Based Learning, Learning Theories*

INTRODUCTION

Learning during Laboratory Work

Imagine you are supervising a laboratory class, and one of your students is about to make a mistake by discarding the supernatant, containing the desired component, instead of the pellet. Despite your exhaustive efforts to make the protocol as clear as possible, there are always students who do not seem to think while executing a protocol. You wonder: how can this phenomenon be explained?

Teaching students how to "do" science in the laboratory can be split into multiple stages.[1] In the first stage, students develop experimental skills and become comfortable and competent in the laboratory environment. This includes practical learning outcomes such as "be able to correctly use a pipet". In the second stage, students learn to predict the effect of changes in protocols and learn to explain their observations. In this stage, theoretical knowledge is added to the already existing practical knowledge obtained in the first stage. The next stages focus on experimental design, initially with familiar outcomes, and ultimately with open-ended and unfamiliar topics.

In this study, we focused on student learning in the first two stages, in which students are typically provided with ready-made protocols. Protocols contain the information required to execute each practical step. But no matter how detailed a protocol is, students might come up with practical questions. For example, the protocol step "Fill three beakers with 2 mL of demi water", can lead to questions such as the following: What size should the beakers be? Which pipet should I use? Which pipet tip is suitable? Should I change the pipet tip in between? Where do I find all the materials that I need? Since protocols generally do not contain answers to all such questions, students will have to make practical choices. In relation to the second stage, students learn (i) to understand the "why" (reason or theory) of protocol steps and (ii) to combine this theoretical understanding with their experience in making practical choices to do troubleshooting in the case they encounter a problem or unexpected situation while executing a protocol.

The success with which students learn during laboratory work is among others influenced by their working experience in laboratories, their prior knowledge, the cognitively demanding environment of a laboratory (for example, caused by having to

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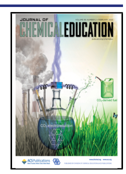

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Table 1. Overview of the Question Types, with Corresponding Aim and Example of a Learning Outcome

Question category	Aim	Example of learning outcome
Theoretical	To improve students' understanding of the "why" (reason or theory) of protocol steps	Understand which components of a sample end up in the pellet, and which components end up in the supernatant upon centrifugation
Practical	To increase students' awareness of practical choices to be made in protocol steps, and to practice making such choices	Be able to choose the appropriate glasswork
Troubleshooting	To help students combine and apply theoretical and practical knowledge to identify and solve (potential) mistakes	Be able to come up with an approach when the pH of a protein solution was increased too much
Data processing	- To improve students' ability to process raw data into results. - To support students' understanding of the reason for protocol steps in which data is gathered (e.g., a weighing step)	Be able to calculate the recovery of protein after isolation

work around fellow students, locating materials, and using equipment), and perhaps most importantly, their own goals for laboratory education. Students were found to be primarily guided by affective goals, as opposed to faculty, who tend to primarily focus on cognitive and psychomotor learning (as also reflected in the first two stages).[2] This means that students are primarily focused on completing the laboratory work as soon as possible, which results in very little meaningful learning during the laboratory work.[3]

Careful student preparation has proven to increase meaningful learning during the laboratory work.[4−6] Students can, for example, prepare with learning materials such as videos, lectures, exercises, and computer simulations.[5,7−12] To the best of our knowledge, such learning materials focus on general understanding of a protocol, without discussing the level of detail: the protocol steps. Especially in terms of the second stage, it is valuable for students to understand the theory behind a protocol step and understand the reason for this protocol step. Without this understanding, students will not be able to make changes to protocols or to do troubleshooting in the case they encounter a problem or unexpected situation.

The aim of this study was to design and evaluate a preparative e-learning material that focuses on protocol steps. The design goal was threefold: to help students to (i) understand the "why" (reason or theory) of protocol steps, (ii) make practical choices, and (iii) do troubleshooting. In the following sections, we discuss the design of the preparative e-learning material (Design of Interactive Protocols), provide a showcase (Showcase of the Interactive Protocols), and present the evaluation results (Evaluation of the Interactive Protocols).

■ DESIGN OF INTERACTIVE PROTOCOLS

Context of the Design

The preparative e-learning material that focuses on protocol steps was designed for the second-year bachelor course "Food Chemistry", taught at Wageningen University, The Netherlands. The course is an introduction to the chemistry of compounds present in food and is attended by approximately 200 students every year. During the laboratory classes of this course, students learn about and execute methods that are relevant to analyze food compounds.

Since the learning material should be accessible for many students at the same time, it was required to be online and interactive. With these requirements, the learning material provides students with specific feedback, and a large group of students will be able to complete the assignment at the same time, with minimal supervision.

Design Choices

Following the design goal and the requirements, interactive protocols were designed. This was done by enriching existing protocols with closed-ended questions. All closed-ended questions are interactive, which means that students can be provided with answer-specific feedback. Four types of questions were designed: theoretical questions, practical questions, troubleshooting questions, and data processing questions. An overview of the question types, with corresponding aim and example of a learning outcome, is provided in Table 1.

In the following sections, we will first discuss *when* to include each type of question, after which we elaborate on *how* to design such questions.

When to Include Theoretical and Practical Questions in Protocol Steps? The choice to enrich a protocol step with interactive theoretical and/or practical questions is based on the often implicit learning outcomes related to protocol steps and on motivational aspects. In terms of the learning outcomes, not all protocol steps can contribute to improving students' understanding of the "why" (reason or theory) of protocol steps or require practical choices to be made. For example, the protocol step "Place the Dumas aluminum sample cups in the sample tray of the Dumas apparatus", did in our case not contribute to the learning outcomes, so we did not include any question for this step. Consequently, such protocol steps are also irrelevant to focus on in troubleshooting or data processing. In terms of motivational aspects, a selection of the interactive questions is prone to repetition. For example, a practical question on how to use a centrifuge may be applicable multiple times in one protocol and may be applicable to several protocols within the learning material. While we acknowledge repetition as a key learning aid, we argue that repetitions should be limited to prevent frustration. For this reason, the maximum of two questions on the same topic were included, for the entire learning material.

When to Include a Troubleshooting Scenario? To help students combine and apply the theoretical and practical knowledge to identify and solve (potential) mistakes, troubleshooting scenarios were introduced. In a troubleshooting scenario, students are presented with a text describing a real-life scenario, followed by pictures of (intermediate) results and/or data resulting from the protocol. At some point in the scenario, an error has been incorporated. In corresponding questions, students are asked to identify the mistake and/or to indicate if the mistake can be fixed, and if so, how. Depending on the context, there were multiple follow-up questions that together form a complete troubleshooting scenario. The decision to include troubleshooting scenarios was based on teacher interviews, which yielded a list of potential mistakes with a significant effect on the outcome and frequently asked questions by students. Based on this list, the troubleshooting scenarios were designed. In practice it turned out that some protocols are not enhanced with a troubleshooting scenario, while other protocols have multiple troubleshooting scenarios.

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Table 2. Design Principles (DP) for Interactive Closed-Ended Questions, Including Explanation and Application

Code	Design principle	Explanation and application
DP1	Include only one new concept per question	To minimize unnecessary cognitive load, the content should be broken down into small segments,[13] which should be presented one by one.[16] Each closed-ended question may contain multiple concepts, but only one of them should be new.
DP2	Avoid including material that does not support the instructional goal	"People learn better when extraneous material is excluded rather than included."[17] All text and graphics that do not support the instructional goal, e.g., background information, or unneeded variables, should be avoided.[13]
DP3	Force students to act	In order to trigger students to actively process the information, the interactive protocol requires students to answer all questions correctly before they can proceed.
DP4	Provide feedback	"Providing feedback is an ongoing process in which teachers communicate information to students that helps them better understand what they are to learn, what high-quality performance looks like, and what changes are necessary to improve their learning".[18] Answer-specific feedback should be given in all closed-ended questions, which should help students to complete the questions independently.
DP5	Provide calculation hints	To guide students' thinking process when doing multistep calculations, they can be provided by hints. The hints can be accessed one by one, so that students can choose to use only part of the support. The hints, together with the feedback (DP4), will take away many questions that would otherwise have to be answered by a teacher.
DP6	Use different question types	As a motivational element, the interactive protocols use a range of question types such as multiple choice, drag and drop, and fill in the blank questions.

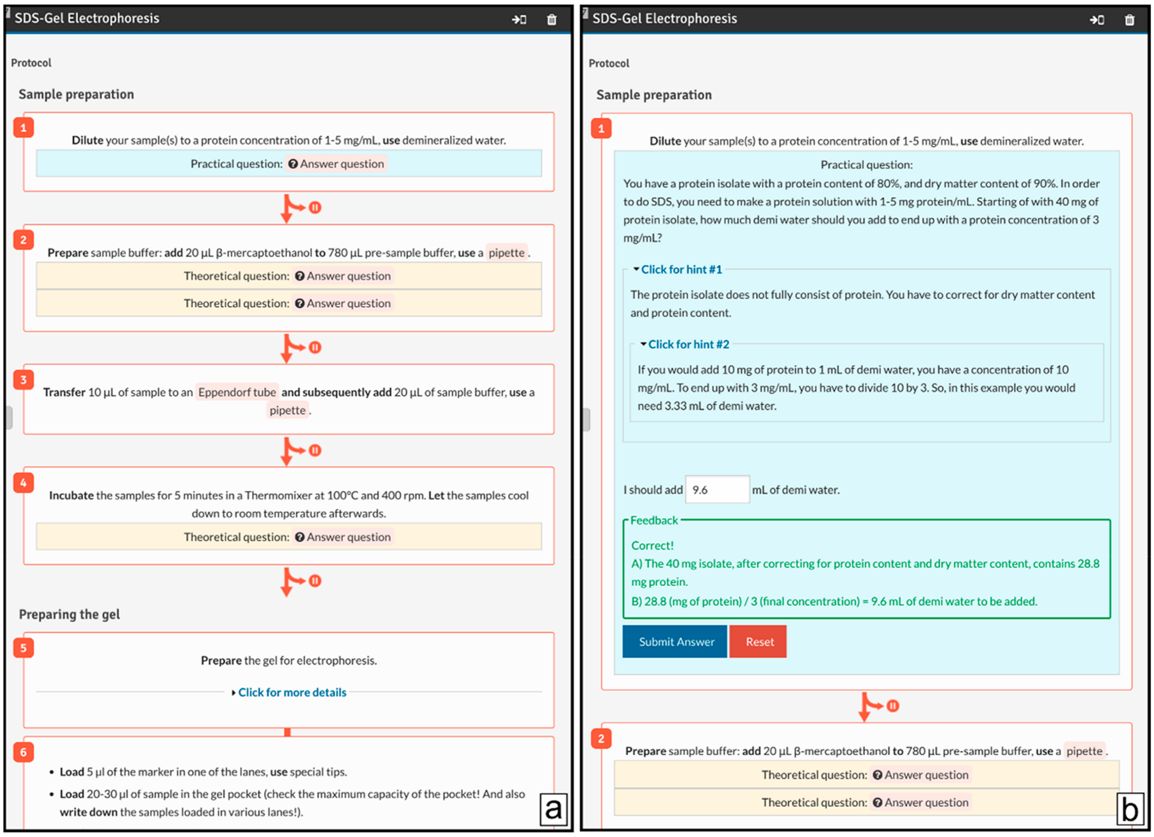


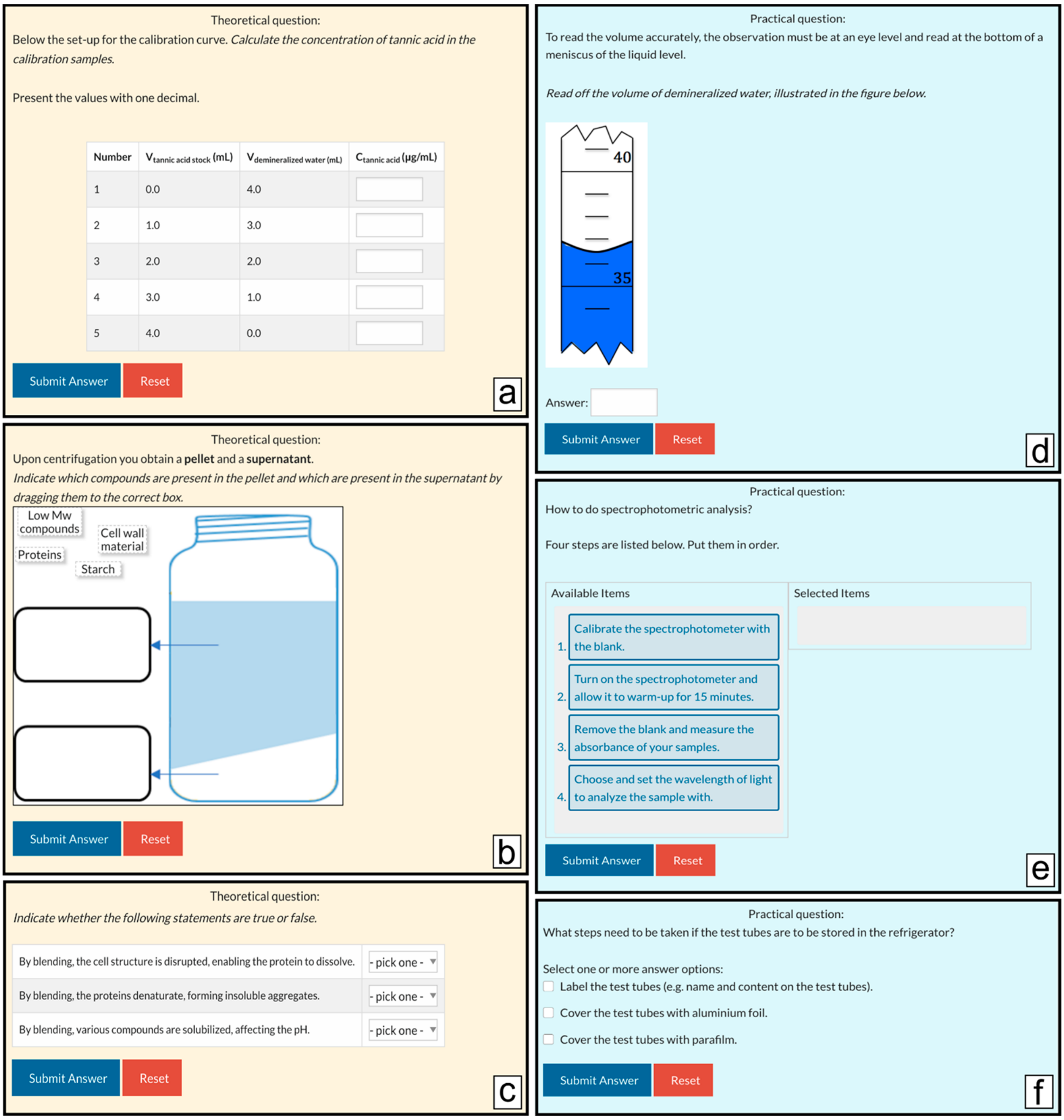
Figure 1. (a) The first part of an interactive protocol with links that will open the question once clicked on it. (b) Opened question in the first protocol step, with visible hints and feedback.

When to Include Data Processing Questions? In case executing a protocol leads to the collection of raw data, students should also understand and be able to process this raw data into results (i.e., by doing calculations). For example, when students know they must do mass balance calculations and understand how these calculations are done, they may better realize why it is important to accurately weigh their samples multiple times while executing the protocol. For this reason, and when appropriate, practice calculations with exemplary raw data were included in the interactive protocols.

How to Design Interactive Closed-Ended Questions? So far, it has been discussed *when* to enhance protocol steps with questions. In this section, the focus is on *how* to design such questions. To design the interactive closed-ended questions, several design principles from literature were applied,[13−15] as shown in Table 2. Note that these design principles are generally applicable to the design of any interactive closed-ended question.

■ SHOWCASE OF THE INTERACTIVE PROTOCOLS

The interactive protocols were built in a platform called LabBuddy (Kryt b.v., Wageningen, The Netherlands) and are illustrated in this section. Figure 1a shows the first part of a protocol, including the interactive closed-ended questions. Initially, all questions are collapsed to provide a good overview of the protocol. When a student clicks on "answer question", the question will open within the protocol step. Figure 1b shows an opened question containing hints that must be opened one by one and shows an example of the feedback provided when a correct answer is submitted.



Number	$V_{\text{tannic acid stock}}$ (mL)	$V_{\text{demineralized water}}$ (mL)	$C_{\text{tannic acid}}$ (μg/mL)
1	0.0	4.0	
2	1.0	3.0	
3	2.0	2.0	
4	3.0	1.0	
5	4.0	0.0	

Figure 2. Examples of theoretical questions (a, b, and c) and practical questions (d, e, and f).

Examples of Theoretical and Practical Questions

In Figure 2, examples of theoretical questions (Figure 2a−c) and practical questions (Figure 2d−f) are shown.

Examples of Questions in Troubleshooting Scenarios

In Figure 3, two troubleshooting questions are shown. The first question describes a situation in which a fellow student loses his/her patience and adds too much NaOH. Then, through this question, advice should be given on how to solve the situation (Figure 3a). The second question is part of a scenario in which a student made a poor calibration curve, asking whether he/she will have to redo the calibration curve alone, or also the samples (Figure 3b).

Example of a Data Processing Question

In this example, a seven-step data processing question in which students calculate protein recovery for two samples is shown (Figure 4a). All intermediate and final calculations can be submitted to the system, which will subsequently indicate for each answer whether it is correct. Furthermore, a worked example, including a visual, is provided as a hint (Figure 4b).

■ EVALUATION OF THE INTERACTIVE PROTOCOLS

The designed learning material consisted of seven interactive protocols and were evaluated in terms of the design goal: to help students to (i) understand the "why" (reason or theory) of protocol steps, (ii) make practical choices, and (iii) do troubleshooting. The seven evaluated protocols consist of a total of 55 protocol steps, which were enriched with 27

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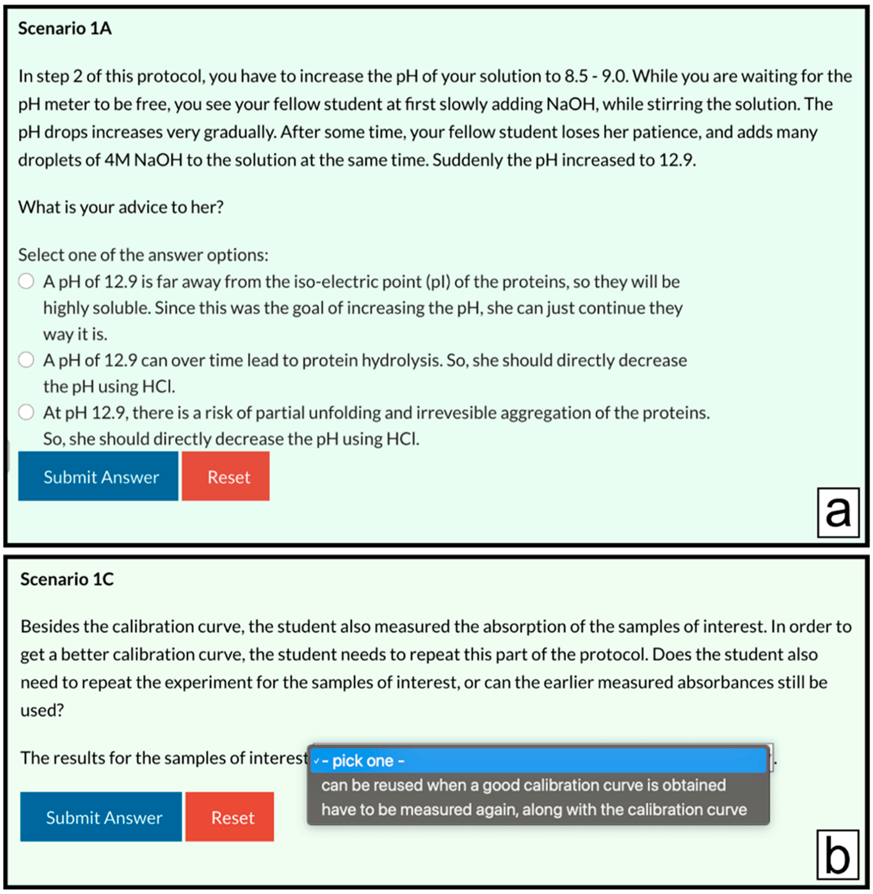

Figure 3. Two examples of troubleshooting questions.

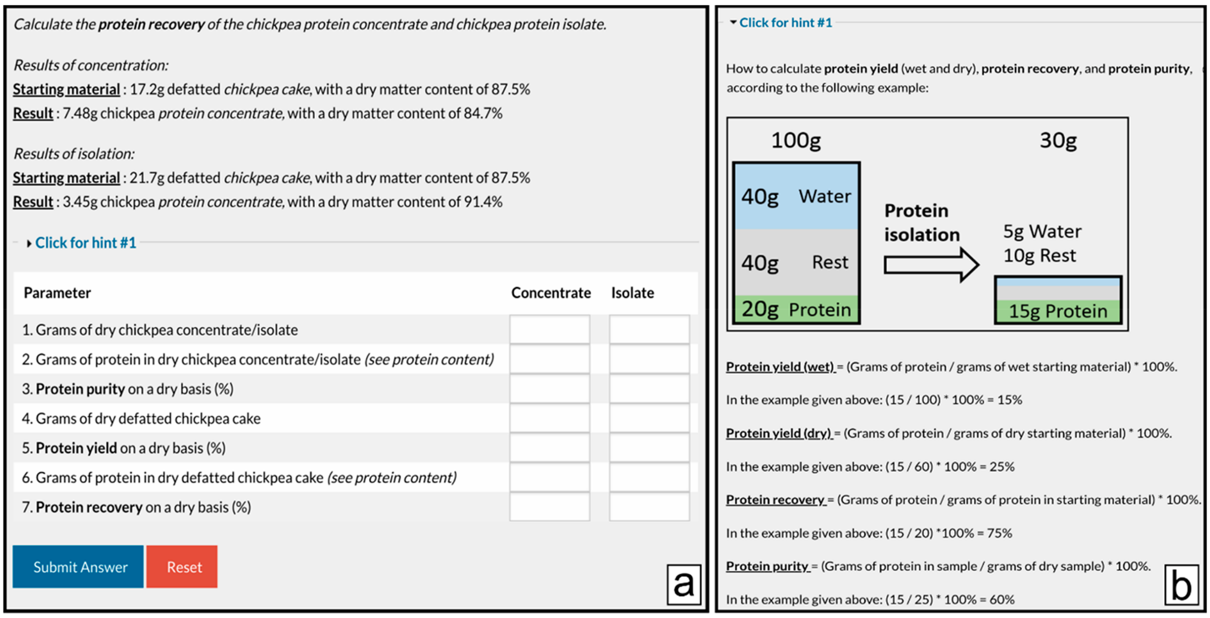

Figure 4. (a) Example of a data processing question. (b) The opened hint, being a worked example with a visual.

theoretical and 11 practical questions. Five troubleshooting scenarios were introduced, which comprised a total of 12 questions. In four protocols, students obtain raw data that must be processed into results by doing calculations. In those protocols, students can enter a total of 36 (intermediate) values in the corresponding calculation questions.

Participants

All students ($N = 200$) were enrolled in the bachelor level course Food Chemistry (168 study hours). The course was attended by students who were enrolled in the bachelor study Food Technology (66%), Biotechnology (10%), or another bachelor program (24%). Students were on average 20.2 (SD = 1.8) years

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old, and 59% of the participants were female, while the others were male; 82% of the participants were Dutch, while the rest had other nationalities.

Procedure

All student activities related to the evaluation procedure are shown in Table 3.

Table 3. Student Activities Related to the Evaluation of the Interactive Protocols

Code	Student activity	Measurement	Day[a]	Duration
A1	Preparative assignment	N/A	1	2 h
A2	Interactive protocols	Student behavior[19]	2	4 h
A3	First questionnaire	Evaluation of design goal	2	5 min
A4	Laboratory classes	N/A	5−9	20 h
A5	Second questionnaire	Evaluation of design goal	9	5 min

[a]Running days relative to the start of the experiment.

Before students started working in the interactive protocols, they first engaged in a preparative assignment (A1). In this assignment, students designed the experiments for the laboratory work that was scheduled for the week after. The preparative assignment and the interactive protocols (A2) were scheduled as compulsory activities prior to the start of the laboratory classes. Upon completion of the interactive protocols, students were asked to complete the first questionnaire (A3), which led to $N = 185$ responses. The aim of this questionnaire was to evaluate each of the four question types (theoretical, practical, troubleshooting, and calculation questions) before students started the laboratory work. All questions had a 5-point Likert scale (1 = disagree, to 5 = agree). On the last day of the laboratory classes (A4), students were asked to complete the second questionnaire (A5), which led to $N = 190$ responses. In this questionnaire, students were once again asked to reflect on the usefulness of the theoretical, practical, troubleshooting, and data processing questions. Only the results from students who filled in both questionnaires ($N = 172$) were included in the analysis.

Evaluation: Was the Design Goal Achieved?

The questionnaire results that were used to evaluate whether the design goal was achieved are shown in Table 4. The design goal was threefold: to help students to (i) understand the "why" (reason or theory) of protocol steps, (ii) make practical choices, and (iii) do troubleshooting.

In terms of the first design subgoal (help students to understand the "why" (reason or theory) of protocol steps), 91% of the students indicated that the theoretical questions in the interactive protocols helped them to understand the reason behind individual protocol steps (Q1.1). After the laboratory classes, a more varying and overall slightly lower level of understanding was reported (Q2.1).

In terms of the second design subgoal (to help students make practical choices), the results show that 79% of the students indicated that the practical questions helped them become aware of the practical choices that must be made during the laboratory work (Q1.2). More than two-thirds (68%) of the students indicated that the awareness they gained by answering the practical questions in the interactive protocols helped them to make practical choices during the laboratory work (Q2.2).

In terms of the third design subgoal (help students to do troubleshooting), 70% of the students indicated that the knowledge they gained by answering the troubleshooting questions would contribute to making fewer mistakes during the laboratory work (Q1.3). However, after the laboratory work, only 15% of the students reported that the troubleshooting questions made them more aware of (potential) mistakes during the laboratory work (Q2.3).

Being aware of (potential) mistakes during laboratory work might be a bridge too far for many second year BSc students. For students to be aware of (potential) mistakes, they should first have a full understanding of the protocol steps. Second, they should be aware of the level of their own skills. Third, they should be able to reflect on their skills while executing a protocol in a cognitively demanding laboratory setting. Last, students should also be willing to think about potential mistakes, while it has been reported that students' focus is typically on completion of the task in the laboratory as quickly as possible.[3] Since many students seem not yet able to or willing to do troubleshooting in the laboratory, it adds extra value to include troubleshooting scenarios to the interactive protocols, so that students will be able to practice troubleshooting.

In terms of data processing, 83% of the students indicated that they were confident that they would be able to process the raw data they would obtain during the laboratory work (Q1.4). This confidence remained after students had completed the actual calculations during the laboratory classes (Q2.4). In line with the results corresponding to the theoretical questions (Q1.1 and Q2.1), the high level of confidence suggests that students also

Table 4. Combined Results of the First (before Lab Work) and Second (after Lab Work) Questionnaires[a]

Code	Short description	Timing of question	1	2	3	4	5	4+5
Q1.1	Theoretical questions - understand protocol steps	Before lab work	0	0	9	77	14	91
Q2.1	Level of understanding of theory behind experiments	After lab work	1	8	18	44	29	73
Q1.2	Practical questions - aware of practical choices	Before lab work	1	6	14	53	26	79
Q2.2	Practical questions - helped to make practical choices	After lab work	2	14	16	48	20	68
Q1.3	Troubleshooting - will make fewer mistakes	Before lab work	1	3	26	52	18	70
Q2.3	Troubleshooting - aware of (potential) mistakes	After lab work	6	53	26	11	4	15
Q1.4	Data processing questions - Confidence in processing data	Before lab work	0	2	15	69	14	83
Q2.4	Data processing questions - Was useful to process the data	After lab work	1	3	20	48	28	76

[a]The values represent the percentage of students ($N = 172$) who selected the corresponding answer option. Shading was used to visualize the distribution of the results. All questions (Q) had a 5-point Likert scale (1 = disagree, to 5 = agree).

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had a good understanding of how to process the raw data obtained by executing the protocol.

CONCLUSIONS

The aim of this study was to design and evaluate a preparative learning material that focuses on protocol steps with the design goal to help students to (i) understand the "why" (reason or theory) of protocol steps, (ii) make practical choices, and (iii) do troubleshooting. To reach this goal, protocol steps have been enriched with theoretical, practical, troubleshooting, and/or calculation questions to form interactive protocols. This design process resulted in a list of design choices (i.e., when to include a question and how to design a question) and a showcase of questions in the interactive protocols. These interactive protocols were implemented and evaluated in a real educational setting. From the evaluation results it was concluded that the interactive protocols were successful in preparing students for the laboratory work. After the laboratory work, students reported a more diverse and slightly less positive contribution of the interactive protocols to their understanding of the protocol steps and their ability to make practical choices. A significant difference was found in the perceived usefulness of the troubleshooting questions before versus after the laboratory work, which is suggested as a topic for further investigation.

AUTHOR INFORMATION

Corresponding Author

Julia Diederen − *Laboratory of Food Chemistry, Wageningen University & Research, 6708WG Wageningen, The Netherlands;* orcid.org/0000-0002-4025-887X; Email: julia.diederen@wur.nl

Authors

Sjors Verstege − *Laboratory of Food Chemistry, Wageningen University & Research, 6708WG Wageningen, The Netherlands*

Wander Lamot − *Laboratory of Food Chemistry, Wageningen University & Research, 6708WG Wageningen, The Netherlands*

Jean-Paul Vincken − *Laboratory of Food Chemistry, Wageningen University & Research, 6708WG Wageningen, The Netherlands;* orcid.org/0000-0001-8540-4327

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.1c00541

Notes

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