JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Technology Report

Mobile Augmented Reality Laboratory for Learning Acid–Base Titration

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Cite This: https://doi.org/10.1021/acs.jchemed.1c00894 Read Online

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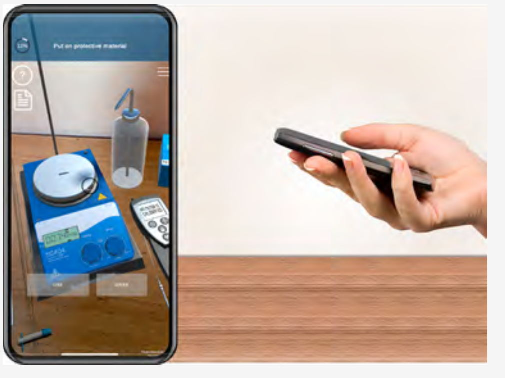
ABSTRACT: Traditionally, laboratory practice aims to establish schemas learned by students in theoretical courses through concrete experiences. However, access to laboratories might not always be available to students. Therefore, it is advantageous to diversify the tools that students could use to train practical skills. This technology report describes the design, development, and first testing of a mobile augmented reality application that enables a hands-on learning experience of a titration experiment. Additionally, it presents the extension of the TrainAR framework for chemical education through the implementation of specific domain features, i.e., logbook, graph, and practical oriented hints. To test the application, 15 participants were recruited from five different high schools and two universities in Belgium. The findings reflect that the MAR Lab app was well-received by the users. In addition, they valued the design elements (e.g., logbook and multiple-choice questions), and the system has "good" usability (SUS score 72.8, SD = 14.0). Nevertheless, the usability and learners' experience can be improved by tackling technical problems, providing more explicit instructions for subtasks, and modifying certain features. Therefore, future development will concentrate on improving upon these shortcomings, adding additional levels to target a larger audience, and evaluating the improvements' effects with more participants.



KEYWORDS: *First-Year Undergraduate/General, Laboratory Instruction, Computer-Based Learning, Hands-On-Learning/Manipulatives, Acids/Bases, Titration/Volumetric Analysis*

■ INTRODUCTION

According to education 4.0, experience-based learning is part of the new paradigms that will enable future professionals to solve tomorrow's problems.[1] This pedagogical approach is at the core of the subject matter for STEM education.

However, new challenges such as the reduction in time and frequency or even the complete removal of practical sessions have raised the need to find new ways to provide laboratory practice to STEM students.

Emerging technologies, such as virtual reality (VR) and augmented reality (AR), have provided alternative hands-on experience in recent years. In chemical education, both AR and VR have been used to support diverse learning activities.[2−9] Specifically for training laboratory skills in titration, VR scenarios have been developed and tested.[10,11] These studies suggest that virtual environments can enhance the learners' confidence when performing chemical experiments, and they can serve as pretraining for real laboratory practice. Similarly, Tee et al.[12] have shown that students could also gain confidence when performing experiments using a marker-based AR titration tool.

When comparing both technologies, AR is considered less intrusive to the user[13] and can be deployed on handheld devices, converting it into an accessible tool for students everywhere.[14] Moreover, data from several studies suggest that the learning benefits of AR are related to the improvement of spatial abilities, the increase of memory retention, the decrease of cognitive overload, and the boost in learners' motivation.[13,15−17] Additionally, AR can positively affect students' academic performance and achievement.[18−22]

On the other hand, the use of AR in educational settings also comes with some challenges. For example, from a pedagogical perspective, it may not always be evident how to integrate the educational content and AR technology.[13,23] Moreover, ensuring that all students can access the learning environments is one of the priorities of schools and institutions.[24] Therefore, this research takes advantage of the TrainAR[25] framework, originally developed for midwifery training, which combines a didactical approach for procedural training with a scalable

Received: August 19, 2021
Revised: January 5, 2022

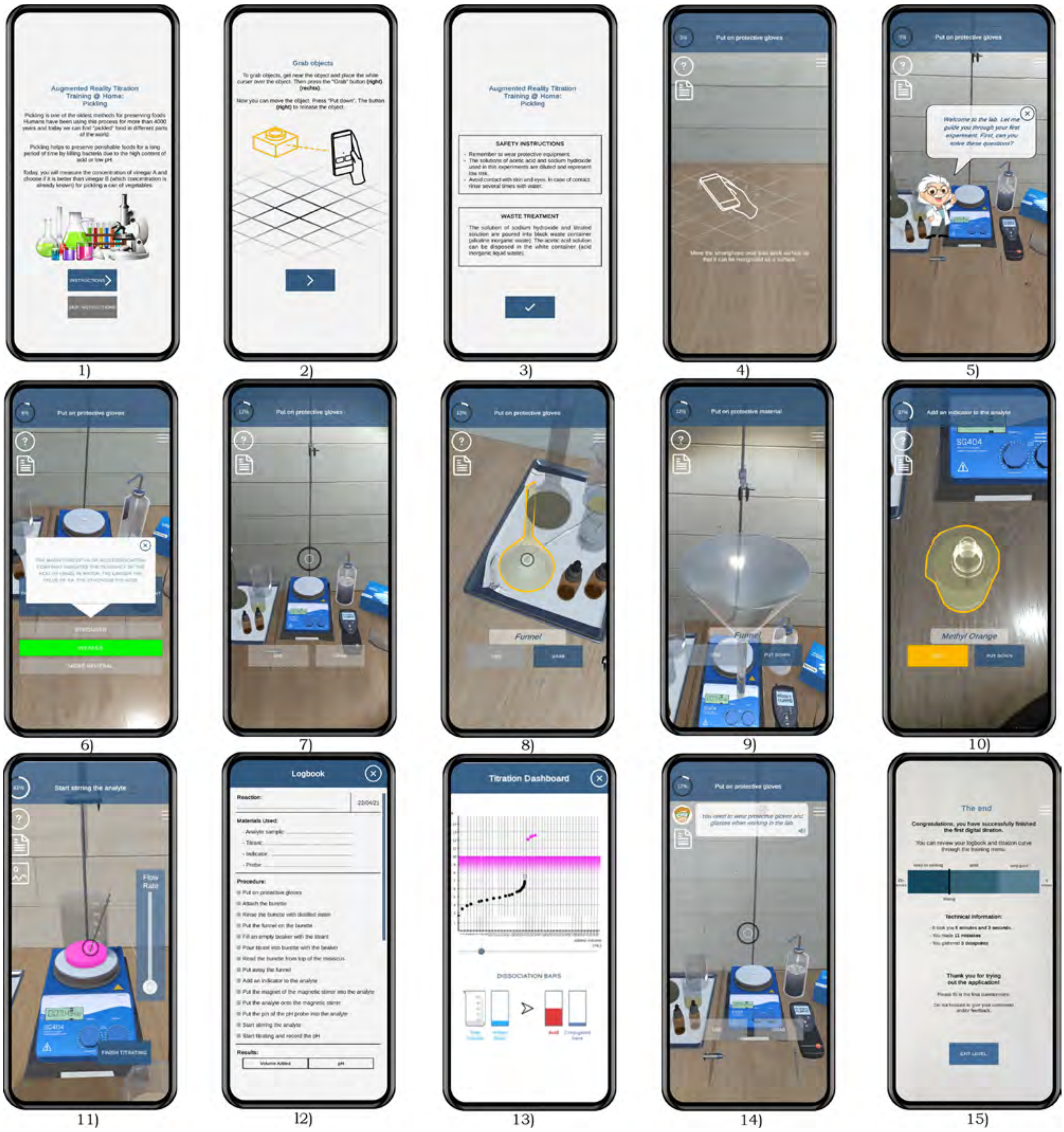


Figure 1. MAR Lab flow and specific features inside the application. (1) Introduction to the chemical context, (2) instructions on how to use the application, (3) safety and waste treatment instructions, (4) scanning of the surface, (5) introduction by the cartoon character, (6) example of multiple-choice questions, (7) virtual content, the crosshairs for the selection and interaction buttons, (8) select interaction, (9) grab interaction, (10) combine interaction, (11) titration slider, (12) logbook overlay, (13) dashboard overlay, (14) hint given after pressing the question mark in the top of the screen, and (15) feedback overlay.

interaction concept for handheld AR devices. By using this framework, we aim to extend its scope and tailor it to teach practical laboratory skills in a scalable fashion.

As part of the EU Horizon 2020 CHARMING project,[26] this report describes the design, development, and first usability testing of the MAR Lab app. The application leverages AR features and enables students to experiment almost like in a real laboratory. However, unlike different approaches, the application is designed to be accessible to students outside traditional settings (lab or classroom) in a remote format through their own mobile devices. Furthermore, it does not require tangible markers and aims to be scalable to different chemical contexts, meaning that the titration experiment is only used as a case study.

The objectives of the research are (1) to develop a tool that students can use to train laboratory practical skills without being physically present in a laboratory, (2) to investigate the usability of the system among high school and undergraduate students of chemical engineering and explore perceived

https://doi.org/10.1021/acs.jchemed.1c00894
J. Chem. Educ. XXXX, XXX, XXX−XXX

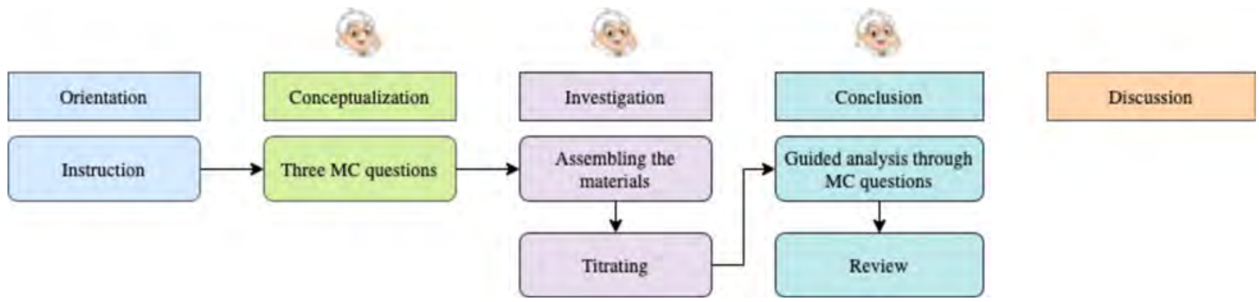


Figure 2. Stages of the application mapped into the inquiry-based learning cycle.[30,31] The cartoon indicates in which phase of the process it appears, either with hints or questions.

usefulness, and (3) extend the scope of the TrainAR framework for chemical education.

■ MAR LAB APPLICATION

The MAR Lab application is a markerless augmented reality application to train students on conducting a titration experiment. The application utilizes the features of augmented reality to allow the learner a more "realistic" environment than a simple smartphone game, meaning that the user interacts with 3D models of the materials present in a real laboratory.

Currently, most AR research is focused on the affordance of "augmenting" the physical world with virtual content and blending both worlds through tangible interactions. However, this prototype stresses an inverted view: the virtual laboratory "augments" the user's physical world and contextualizes the content into the physical reality without tangible markers. Our approach ensures that the content can still be accessible to most users because the environment only has basic physical requirements (e.g., users do not need to print a marker or need the real object), but interactivity is still present. Moreover, the design is supported by recent evidence suggesting that knowledge transfer and increased retention are not necessarily increased when tangible interactions are compared with purely virtual environments.[27]

■ APPLICATION DESIGN

Rapid prototyping[28] and the Design Implementation Framework (DIF)[29] were utilized during the design and development of the app. Unlike other frameworks, DIF acknowledges usability and user experience as part of the learning experience and implements feedback and evaluation at various points of the iterative cycle.

The iterative process began with the definition of the educational need with the expert panel and ideation of the prototype. Subsequently, a low-fidelity prototype was created and evaluated. For this process, 15 students of the General and Technical Chemistry (*Algemene en Technische Scheikunde* B-KUL-H01A8A) course at KU Leuven participated in a think-aloud study, and 85 participants answered a survey (Supporting Information). The think-aloud study helped solve possible ambiguities of the design elements. For example, some users did not understand the icons or the buret's interaction.

Additionally, the survey results ensured that the design decisions were tailored to the end-users. The primary outcomes included language selection (English), main functionalities of the application (e.g., redo, quit, review, menu, etc.), the addition of initial onboarding, and the use of the cartoon character. As a result, design decisions were implemented in the digital prototype.

Finally, the digital prototype of the MAR Lab app was created using the TrainAR framework.[25] This framework proposes a combination of interaction concepts, a didactic framework, and a unity-based authoring environment to create procedural handheld augmented reality trainings. Hereby, an early version of the authoring tool, based on ARFoundation, a markerless-tracking library utilizing ARKit and ARCore on iOS and Android smartphones, was used in Unity Version 2019.4. This approach was chosen to leverage familiar handheld MAR metaphors to create procedural task-based training based solely on virtual content across differing levels of media competency.

It is important to note that some of the features of the MAR Lab app were not present in the original framework. The domain-specific extensions include using the logbook, graph, or experimental chemical hints given by the cartoon. These elements ensured that the educational need was fulfilled and, as a result, extended the use of TrainAR for chemical education

■ APPLICATION FLOW

In line with the TrainAR[25] framework, the experience starts with explaining the context of the application and the task to be performed by the student; this step is referred to as "onboarding" (Figure 1, panel 1). Subsequently, an optional tutorial on how to use the application is provided (e.g., showing how to interact with the objects, Figure 1 panel 2). Before starting the "experiment", both safety and waste treatment instructions are shown (Figure 1, panel 3). The experiment starts when the user scans a table surface in the real environment, and the virtual laboratory is deployed in the scanned area (Figure 1, panel 4).

The user can start the experiment by moving, selecting, grabbing, and combining the materials (Figure 1, panels 8–11). At the top of the screen, instructions about steps that need to be performed are given. For example, if the student combines the wrong objects, the system provides real-time feedback with a sound signal and an outline surrounding the materials (Figure 1, panel 10). Finally, correct steps performed by the user during the experiment are recorded in the logbook (Figure 1, panel 12), and incorrect actions are stored to provide feedback at the end of the experiment (Figure 1, panel 15). The experimental measurements (pH vs volume of titrant) are visualized in a graph (Figure 1, panel 13).

The application flow elicits four general phases of the inquiry-based learning cycle[30,31] (Figure 2).

(1) The orientation phase is depicted with the learning module's instruction.

https://doi.org/10.1021/acs.jchemed.1c00894
J. Chem. Educ. XXXX, XXX, XXX−XXX

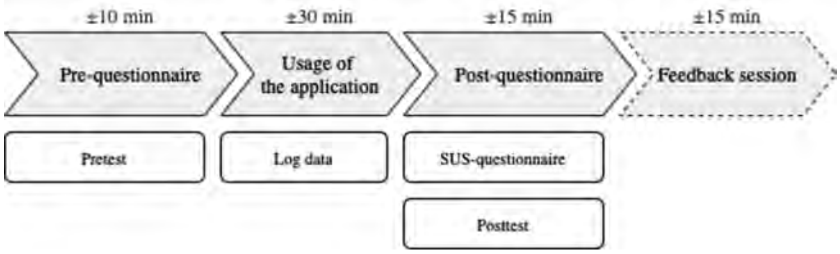


Figure 3. Overview of the user study and the time spent on each phase with each participant. The dotted line indicates that the phase was voluntary.

Figure 4. SUS score compared on the scale of Bangor et al.[39] The mean score for MAR Lab is 72.8 (SD = 14); thus, it can be considered good and in the acceptable range of usability.

(2) The conceptualization phase includes multiple-choice questions posed to the learners by a cartoon character before the experiment (Figure 1, panels 5 and 6). These questions aim to activate prior knowledge of the user and test their understanding during the experience.[32]

(3) The investigation phase comprises 16 steps in total. These steps include assembling the materials, titrating, and "cleaning" the environment. The cartoon character provides hints in this phase.

(4) The conclusion phase is a guided analysis by the cartoon character after completing the experiment, through multiple-choice questions. A review screen is made available at the end of the training.

The MAR Lab application is based on experiential learning[33] and embodied learning theories[34] which aim to incorporate a deeper understanding and improve students' participation in learning by eliciting bodily actions (e.g., the user must move their hands and their bodies to interact with the lab materials). The hands-on experience through concrete activities with virtual objects emphasizes the concretization of actions that may be suited to teach complex scientific concepts.[35] Additionally, the actions performed in the MAR Lab application aim to improve the sense of control while using the application. By providing control to the user, the app aims to enhance the enjoyment of the experience related to the learner's engagement.[36]

The interaction with the objects simulates the natural actions such as grabbing, reading, pouring, observing, mixing, etc., done in real settings, thus reducing the need of the user to construct a context in real-time and allowing more engagement during the learning experience. Additionally, the interface guides the users through the experiment and provides contextualized chemical information and additional forms of representation of the phenomena observed during the titration experiment (e.g., change in pH, dissociation of acids and bases, and graph). After completing the experiment, the students can use these additional representations to analyze and reflect upon the abstract chemical concepts of the learning module.[31]

The case study developed for this application relates to acid–base titration. This topic was chosen as it is one of the typical experiments done in introductory courses of both high school and undergraduate curricula. Furthermore, as reported by other scholars,[37] practitioners at KU Leuven noted that students struggle to understand the underlying chemistry behind the titration experiment and thus hypothesize that a "practical" experience will remedy this difficulty.

The current prototype comprises one level in which the learner is tasked to "perform" a titration of a weak acid (acetic acid) with a strong base (sodium hydroxide). The specific learning objectives were defined under the guidance and supervision of two lecturers of the General and Technical Chemistry (*Algemene en Technische Scheikunde* B-KUL-H01A8A) course at KU Leuven. These learning objectives were realized using the revised Bloom's Taxonomy,[38] which can then be matched with a specific type of assessment. The goals include both practical and cognitive skills, and they are

- to identify and remember the materials of a titration setup
- to explain the function of the different components of a titration setup
- to assemble and operate the experimental setup
- to interpret, illustrate, and assess qualitatively the titration curve
- to calculate the concentration of the unknown solution

https://doi.org/10.1021/acs.jchemed.1c00894
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■ APPLICATION TESTING

All of the data collection and interaction with participants were performed online. Fifteen participants were recruited from five different high schools and two universities in Belgium. Before starting the study, ethical clearance was granted from the ethical committee in KU Leuven G-2021-3236-R2(MAR). The goal of the test was to explore the usability of the application and the learning outcomes and receive feedback regarding the user experience. The application was made available as a beta version in the Google Play Store (Supporting Information). In total, nine participants completed an SUS questionnaire, an invariant pre-/post-test through a web-based survey tool (Qualtrics), and four users participated in an optional feedback session. The overview of the study can be found in Figure 3. Unfortunately, six users had difficulties downloading the application because the device either did not support the AR capabilities required (i.e., the phone lacked a gyroscope) or did not have enough memory available for the app to be downloaded. Therefore, only the results from users who completed the questionnaires are reported here.

■ RESULTS AND DISCUSSION

The SUS questionnaire was used to explore the usability of the system. Figure 4 shows the SUS score on the scale proposed by Bangor et al.[39] The mean SUS score for the MAR Lab is 72.8 (SD = 14.0). According to this scale, the result can be considered "good" with acceptable usability. These results align with the first usability studies conducted to develop the TrainAR[25] interaction framework, which also uses explicit interaction with buttons.

The user's interaction with the system was collected through Unity Analytics. The data collected included time spent with the application, the number of hints provided during the titration experiment, the number of interactions with the logbook, and the number of mistakes in the multiple-choice questions (Table 1).

Table 1. Results Log Data

log data recorded	time spent (min)	hints (total = 16)	interactions with the logbook	mistakes of MC questions (total = 7)
mean (N = 9)	45	17	11	3
SD	19	14	6	2.7

The invariant pre-/post-test was designed to test participants' knowledge of acid−base concepts and titration. The test contained 11 multiple-choice questions (Supporting Information). t tests found no significant differences in mean scores on the pre- and post-test (p = 0.11). Thus, we conclude that there were no significant learning effects due to platform use. The small sample size may explain this result. However, tackling the shortcomings identified through the data collected may help improve the system so that learning gains can be shown with a larger sample size in later stages of the development of MAR Lab.

The final stage of the study comprised a feedback session with voluntary participants. They were asked about the interaction with the application, the simulation length, their opinion of the design elements (graph, multiple-choice questions, and logbook), and their general experience while using the application.

A common view among interviewees was that interacting with the virtual objects through the buttons on the screen was easy and intuitive (Figure 1, panel 7). Although some participants expressed that they experienced some struggles with specific objects (e.g., floating objects or difficulty seeing through the buret), they were not indicated as major issues, which is also supported by the SUS score. Interestingly, looking at the interaction with the system through the log data, it was observed that some of the steps might not have been clear to all of the students. For instance, the average number of hints among users was 17 (Table 1), which is higher than the total number of hints the system had (16 hints for 16 steps). However, a detailed analysis revealed that during the step of "add an indicator to the analyte", students received the most hints. Therefore, the interaction in this step may be simplified and the hint rephrased to be more specific. Similarly, users expressed in the feedback session that the "cleaning" step was confusing; therefore, the instruction should be revised.

When asked about the logbook and the multiple-choice questions, the participants agreed that both elements were useful and well-received. For example, one participant commented the following on the logbook: "I could find everything I needed." This comment can be supported by the number of interactions with this element among other participants (Table 1).

Another interviewee, when asked about the multiple-choice questions, said "They let you think about the theory but guide you with possible answers." This comment may support the fact that the multiple-choice questions helped users activate their knowledge or helped them reflect. On the other hand, one user pointed out "I thought I was finished, but then I realized I also have to perform the cleaning steps." Therefore, improving this element may be beneficial for more users and may help them understand the theoretical concepts that need to be conveyed by the system. For instance, the wording, the number of questions, and the timing are some aspects that can be improved.

When asked about the general functionalities, the participants agreed that the application contained many functions, and therefore, it was overwhelming at the beginning. These results were in line with previous research, which has established that AR in some cases can be distracting and cognitively demanding for students.[15,16] However, the improvement on the application design and additional onboarding may help reduce the overload and profit from AR features.

In summary, these results provided important insights into what users had experienced and allowed us to rationalize what aspects of the current design can be improved in the next iteration. Specifically, the icons for the logbook and the graph will be simplified by seamlessly integrating the functions as one object (a virtual notebook). This modification will allow the users to interact with the functionalities as part of the environment and avoid having extra icons on the screen.

The interaction with the multiple-choice questions will be improved by excluding this element from the AR environment. Although the questions aim to trigger the conceptualization phase of the inquiry-based cycle and guide the conclusion phase, they may hamper the user experience by interrupting the flow of the application. Therefore, like other authors,[31] the AR environment exclusively will support the investigation phase of the inquiry-based cycle.

https://doi.org/10.1021/acs.jchemed.1c00894
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Finally, apart from the technical issues to be solved (e.g., floating objects and liquids disappearing), instructions as "voice over" for the cartoon character will be added to improve the clarity of some of the steps and help the users with redundant information in a different format.

Regardless of the limitations of the current design, when asked about the experience with the application and its use, the qualitative feedback provided by the students showed that the technology is innovative to them, and they recognized that the application could be helpful when learning experiments like titration. Furthermore, it brings diversity in delivering the chemical and procedural knowledge taught in the curricula. However, it is important to consider that the results are only preliminary due to the limited sample size. In this report, we can only conclude that the system has acceptable usability. Without a doubt, a study including a larger sample size is needed to test whether, apart from the perceived usefulness, this approach is effective for training practical skills when students cannot have access to a laboratory or as a pretraining tool when they do have it.

FUTURE WORK

The future development of the MAR Lab includes improving the aspects acknowledged by users in this study and creating additional levels to enhance user experience and learning gains. These levels will consist of more titration cases and will be contextualized as one problem. Moreover, future research is required to determine how the students learn with the MAR Lab app and if the knowledge learned in the environment can be transferred to real-life situations.

Further work can also evaluate the extension of the prototype for its use by other age groups (secondary school) and educational backgrounds (chemistry apprentices, chemistry students) and assess how to incorporate the prototype as a tool into the chemical engineering and chemistry curricula.

CONCLUSION

This report presented the MAR Lab app's design, development, and preliminary test. This mobile application was designed to enable the ubiquitous practice of laboratory skills in the context of high-school and undergraduate chemistry courses.

As part of the iterative design cycle, domain-specific elements such as the logbook, graphical representations, and practical hints were identified and used to fulfill the educational need. These elements can be used as guidelines for creating new experiences using the TrainAR framework in the context of chemical education.

While preliminary, the current results suggest that although students experienced technical difficulties (unstable tracking, compatibility with devices, floating objects, etc.), the tool has acceptable usability. Moreover, students could use the application independently, i.e., they could finish the training in a remote setup without supervision. The sample size limited this study; however, the students who tried the application were optimistic about the tool's novelty and its use for chemical experimentation.

The next iteration of the development process will improve the system by tackling the identified technical shortcomings and adding additional content. Future iterations will be tested on a larger audience to validate how embodied actions performed in MAR Lab improve procedural knowledge acquisition, the conceptualization of chemical concepts, and the transference of knowledge to real-life settings.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00894.

Low-fidelity prototype (PDF)
Instruction to install MAR Lab app (PDF)
SUS questionnaire and invariant pre-/post-test (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Horizon 2020 Programme under Grant Agreement 812716. The authors would like to thank Prof. dr. Ilse Smets for her continuous support and valuable input, and to all participants for their interest in the project and their feedback.

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