JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Article

Microcomputer-Based Laboratory Role in Developing Students' Conceptual Understanding in Chemistry: Case of Acid–Base Titration

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Cite This: J. Chem. Educ. 2022, 99, 2548–2555 Read Online

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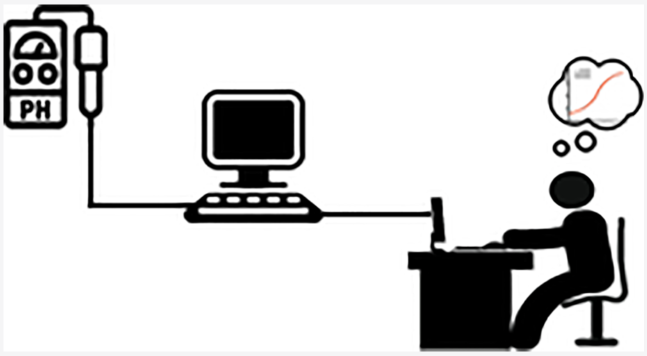


ABSTRACT: For the past five years, all Moroccan universities suspended practical work activities in the subject of chemistry for the first year due to a decision made by the Ministry of Higher Education. This study explores the effect of using a Microcomputer-Based Laboratory (MBL) on students' performance and investigates the desirability to convert first-year university-level practicals in chemistry from experimental demonstrations in lectures to the MBL. The study sample comprised 100 students attending the first year at the faculty of sciences of the Cadi Ayyad University (UCA) in Morocco. Students in the experimental group ($N = 50$) received a 1 h active engagement tutorial on acid–base titration using a microcomputer-based laboratory, in contrast to the control group ($N = 50$) who received the same instruction with a demonstration of the experiment. The experimental and control groups got randomly selected, and the same instructor trained both groups. The two groups of responders were compared based on their performance in a written exam that assesses the skills of processing, analyzing, and interpreting qualitative and quantitative experimental results of acid–base titration. As a result, the analysis of the obtained results showed that the experimental group performed significantly better in using appropriate mathematical skills for quantitative data analysis; and they were actively engaged in the acid–base titration experiment. The obtained results, together with similar findings from other studies, indicate the positive impact of using MBL on learning outcomes and support the adoption of the proposed learning environment in laboratory educational procedures as an alternative to traditional laboratories.

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

■ INTRODUCTION

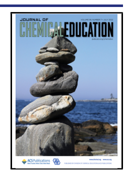
Every year, millions of students worldwide participate in science experiments in different fields to help them learn new skills and verify equations in textbooks and classroom lessons. Experimental activities in science education are fundamental; curriculum developers and teachers recognize the importance of these activities.[1]

Practical works have evolved gradually over the years, and they continue to develop. This evolution is related to changes in the goals of science education and advances in educational technology. The goals of science education supported by laboratory activities include understanding science concepts, interest, motivation, hands-on science skills, problem-solving, and understanding the nature of science. In addition, several research studies have focused on the contribution of scientific experimentation; we can summarize these into three different categories:

- the nature of science: understanding the things used to conduct life, knowing how scientists work
- skills: mastering analytical techniques, critical thinking and problem solving, concrete representation of different concepts
- attitudes: open-mindedness, objectivity, curiosity, participation in teamwork

Since the 19th century, hands-on laboratory work has become essential in science education. In particular, many researchers have suggested that laboratory sessions should not only serve to confirm and illustrate hypotheses learned in the

Received: December 21, 2021
Revised: June 2, 2022
Published: June 17, 2022



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J. Chem. Educ. 2022, 99, 2548–2555

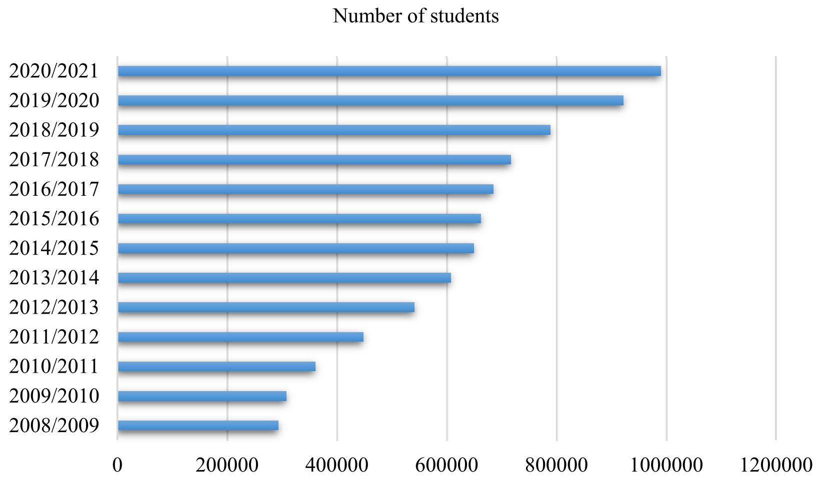

Figure 1. Number of enrolled students at open access universities in Morocco.

course but should be merged with theoretical work in the sciences to develop data through illustrated investigations in the course.[2] In addition, laboratory activities, when done correctly, provide students with the opportunity to "investigate the natural world, propose ideas, [and] explain and justify claims based on evidence from scientific work" in the same way that scientists conduct an authentic investigation.[3] In recent years, emphasis has been on improving science education to develop the knowledge and skills needed in modern society. In addition, globalization and rapid technological development have substantially influenced educational systems, professional training of scientists, and scientific research.[4]

Today, laboratory experiments continue to be an essential part of science education. They have particular well-defined objectives such as to get students interested in the subject and to help them better understand the science lessons, to use a measuring device, to evaluate the uncertainty of experimental measurement, to draw a graph, etc.

In contrast, in the traditional lab session, all of the elements concerning the theory and experiment are provided in the lab sheet text. The document tightly guides the questioning phase, and, in most cases, the student does not have to conduct a literature search. As a result, students rarely get the chance to use high-level cognitive abilities or discuss crucial scientific information. The experimental protocol and measurement operation protocol are provided; the pedagogy adopted is limited to applying "cookbook" type procedures.[5]

Ideally, an inquiry-based approach is implemented in which students have the opportunity to plan an experiment, ask questions, hypothesize, and replan an experiment to test or reject their hypothesis. At the same time, teachers must explicitly link the lab activities, materials, and instructional strategies to the desired student learning outcomes to ensure that the lab experiences align with the stated learning objectives.[2]

Context of the Study

Recent years have seen an increase in the number of students applying for higher education worldwide. In addition, the number of student enrollments has drastically increased over the past decade in Morocco. Figure 1 presents the evolution of the number of enrolled students in open-access universities in Morocco.[6]

The number of students in universities continues to grow. According to provisional statistics from the Ministry of National Education, Vocational Training and Higher Education and Scientific Research in Morocco, the overall number of students in open-access institutions rises to 858,502 in 2020–2021 and 131,397 in limited-access institutions, bringing the total number of students to 989,899.[6]

The problem facing university science education is establishing pedagogical approaches to cope with the increase in the number of students without altering the quality of the training. Moreover, because of the lack of equipment and the high number of students enrolled each year, the Ministry of Higher Education in Morocco has had to drastically reduce the content of the curricula in the subjects taught, reduce the number of hours of lectures and tutorials, and eliminate the practical work for the first year in all of the open-access establishments.[7,8]

These changes made us feel the need for a radical step forward to make things progress quicker and more adapted into a specific and practical objective. We need a significant breakthrough: to create a new paradigm that complements the existing ones, to change alongside the users of the system, and to evolve as institutions (companies, universities, user associations, unions, governments) and as individuals and not always be behind them.[9]

There are so many resources, services, and approaches to complement, enhance, and move science and education forward at present: open science,[10,11] microcomputer based laboratory,[12] open educational resources,[13,14] MOOCs,[8,15,16] virtual reality,[17−19] augmented reality,[20,21] emotional intelligence,[22,23] personalized learning environments,[10,24] serious games,[25] analytics,[26] blockchain,[27] virtual laboratories,[28−30] and so on.

Meaningful Learning in the Chemistry Laboratory

In chemistry curricula, lectures and demonstrations emphasize students' ability to remember information and use it to solve problems, which means they must perform direct calculations. Even when students are allowed to do experiments in the lab, they are given instructions on what to do.[31] Generally, the practical sessions in the laboratory complement the chemistry lectures and deepen the students' understanding of relevant concepts.[32,33] Also, it is important to keep in mind that the fundamental purpose of laboratories is to help students make connections between the real world of objects, materials, and events and the abstract world of thought and ideas.[5,34,35]

https://doi.org/10.1021/acs.jchemed.1c01254
J. Chem. Educ. 2022, 99, 2548−2555

The fundamental course of the first year in analytical chemistry covers important titrimetric methods: acid−base, chemical equilibrium, and redox titrations. Titration remains one of the oldest tools in analytical chemistry and continues to be an essential component of the chemistry student experience. It can be learned in lectures and tutorials and on the bench in practical work. The practical works are not overly complicated; they require an understanding of the underlying chemistry and are considered a simple technique for determining the concentration of an acid or base, but sometimes an essential scientific and pedagogical aspect is entirely overlooked because of the reduction of acid−base reactions to simple mathematical operations unrelated to chemical reality.[36] The teaching of calculations is not enough to understand titrimetry since when students succeed in the numerical questions, they fail to understand the effect of equilibrium at the equivalence point.[37] Therefore, students must have practical and theoretical knowledge of chemical content to propose models by asking questions and generating hypotheses.[38]

The Use of Microcomputer-Based Laboratories in Science Education

Hands-on activities have evolved gradually over the years, and they continue to develop. This evolution is related to changes in the goals of science education and advances in educational technology. Laboratories are excellent places to teach and learn science, especially since they provide students with opportunities to think, discuss, and solve real-world problems. It is hard to imagine learning to do science, or even learning science, without doing lab work.[39] In particular, many researchers have suggested that laboratory sessions cannot just confirm and illustrate hypotheses learned in the classroom but merge with theoretical work in the sciences to develop data through illustrated investigations in the course.[2] However, several weaknesses in the design, execution of processes, and procedures in the laboratory are detected.[40] Most notably in the safer "cookbook" approach, students follow exact instructions without comparing their predictions and observations from experiments.[41] The ideal is to implement an inquiry approach, in a way that students have the opportunity to plan an experiment, ask questions, formulate hypotheses, and then replan an experiment to test or reject their hypothesis. At the same time, teachers need to explicitly link lab activities, materials, and instructional strategies to desired student learning outcomes to ensure that lab experiences are consistent with stated learning goals.[2] Many scientific educators who employ a constructivist approach to education have highly suggested using MBL technology to improve laboratory work.[42,43]

MBL includes a computer associated with an interface and various sensors. It allows measurement in real-time variations of several parameters. Moreover, the students can use probes to collect, record, and graph data to support the constructors of their science concept. In addition, the computer takes care of the technical aspects by facilitating data acquisition and by helping with analysis.[44,45]

MBL has a privileged place in the practice of experimental sciences; it is a quantitative instrument designed to measure changes in the physics-related graph interpretation skills and kinematics conceptual understanding of undergraduate students.[46−48] Some studies on the effects of computer-aided graphing have shown that using MBL improves student ability in working on graph- interpretation tasks. Other researchers, however, think that the traditional way of conducting laboratory experiments by accumulating experimental data to transcribe them into a graphical form may not be effective and does not allow the student to link the experimental data with graph.[49] Phillips' study has argued that if we used computers as a designed graphical display, they might function as a memory aid. He said:

> *"...When the information is spread out in front of us in a graph or a diagram, there is no longer any need to store the raw information inside our heads... The graphical image itself becomes a kind of memory store for as long as our eyes continue to look at it."*[50]

On the other hand, Aksela's research sees the microcomputer-based laboratory as a student-centered learning environment that engages students in meaningful learning and higher-order thinking through inquiry.[51]

Furthermore, MBL could give chemistry education a new dimension; the students are more involved in the learning process because they can focus on the subsequent interpretation and evaluation of graphical data. It also motivates students to study chemistry, including the simultaneous chemical phenomena with graphs.[42] In addition, MBL can promote meaningful chemistry learning and further thinking through cooperative learning and a learning cycle approach.[51] MBL can also allow students to repeat experiments, generate more data for analysis, and help understand chemical reactions in the classroom. Additionally, MBL can collect data in less time because of the immediate feedback.[52] Other researchers discussed how the use of MBL could cause difficulties in interpreting significant features of the experimental data and that students will not have the appropriate skills to record and present the experimental measurements in a suitable format, such as graphs.[53,54] That is not the case for us at UCA (Cadi Ayyad University) because students who go to the university already have a good background and knowledge of these skills during their high school chemistry studies.

The interest of this study is to show the contribution of experimentation in the teaching of chemistry and to know the potential of using an inquiry approach linked to microcomputer-based laboratory experiments to improve laboratory work in the chemistry classroom. All this while bearing in mind the increase in the number of students through reduction of analytical chemistry experiments duration from 4 to 2 h or less using the MBL.

■ METHODS

The study reported in this article was conducted at the UCA, Marrakech, Morocco, as part of first-year chemistry practical teaching. This study conducted MBL activities for acid−base titration. A total of 100 freshman students voluntarily took part in this study. We had two treatments: one conducted 1 h of practical work using MBL, and the other held a lecture explaining the traditional experiment. Students had the right to choose whether to participate in this study or not, and we informed them that the test results would not count in their final score. It was a specification criterion that students must be in the first year and taking the analytical chemistry course for the first time. Students were randomly divided into experimental groups (N = 50) and control (N = 50). The same instructor instructed both groups to control the teacher variable. In the first part, both groups were treated the same way to learn the basic knowledge of acid−base titration and

https://doi.org/10.1021/acs.jchemed.1c01254
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neutralization courses, distinguish between a physical and chemical transformation, and define the concept of reactant and reaction product. Students in the experimental and control groups were treated differently to learn about titration in the second part. Schematically, the research design is presented in Figure 2.

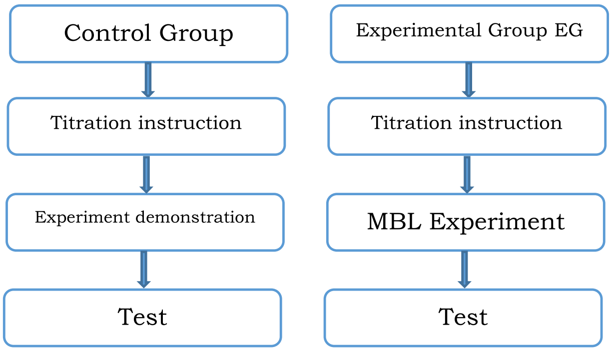

Figure 2. Research design.

Before removing the experiments from the university's first-year practical work, students traditionally performed titration experiments. In the acid−base titration experiment, we drop the base (sodium hydroxide) with a buret at times and record the pH. Then, students construct the pH versus volume of the titrant plot via a spreadsheet with pencil and paper, to determine the unknown concentration of the vinegar as shown in Figure 3.[55]

The acid−base titration experiment is demonstrated for the control group. Given the description of this experiment, students formulate possible explanations and predict the graphs of the titration. It was a mainly teacher-centered approach involving a talk and chalk session and the performance of the traditional titration.

The experimental group performed a 1 h active engagement using the PASCO interfaces and pH meter probe to collect data in real time. The measurements are performed automatically with a PASCO data-acquisition system[56] and the DATA STUDIO software.[57,58] Students performed this pH-metric titration in a laboratory setting. At the beginning of the activity, the instructor demonstrated the correct method to manipulate the PASCO interface and probes.[59] This activity aims to determine the molarity, density, and percent by mass of acetic acid in (CH_3COOH) vinegar. It involves performing a reaction between a solution of an aqueous solution of ∼0.1 M sodium hydroxide (NaOH) (the titrant) and a solution of an unknown concentration "the vinegar" (the analyte). The MBL experimental setup used in this study is shown in Figure 4.

Moreover, to reduce the effects of other variables in the titration experiment, we calibrated the pH meter in advance. We used a drop counter to precisely record the number of drops of titrant added during a titration, which is automatically converted into volume. The sodium hydroxide is gradually added to the vinegar in small amounts from a buret until reaching the end point. The resulting solution at the equivalence point contains soluble sodium acetate. The acetate ion reacts as a base with water, producing hydroxide ions, and the resulting solution will have a pH higher than 10. Students used the computer to both acquire and analyze the data from the experiment. We used this activity as a demonstration to find out if the strength of the vinegar is the same as what a company claims it be in each part of the activity; students make a prediction and give their explanations. Also, students were expected to use their knowledge and understanding to ask scientific questions which can be investigated through experiment activities because we needed them to understand what they were looking for and not just follow specific rules. Therefore, they were encouraged to think carefully about the procedure they were performing.[60] Table 1 shows the questions of the assessment.

■ RESULTS AND DISCUSSION

The test objective is to know the students' performance in the treatment, analysis, and interpretation of qualitative and quantitative experimental results and mathematical skills appropriate for the study of quantitative data. In total, 100 copies of the test were collected, from the experimental group (N = 50) and control group (N = 50). The test has open-ended questions related to the acid−base titration experience. We classified the questions in Table 1 into eight items; we tested one ability in each item. For the four first questions, if the answer was correct, the students scored 2, while for partially correct answers, they scored 1, and they scored 0 for incorrect answers or no answer. For the rest of the questions, the students scored 3 for correct answers. We detailed the tested skills and the number of correct answers in each group, as shown in Table 2.

The test results show that students in both groups answered the first four questions well; it demonstrates their ability to

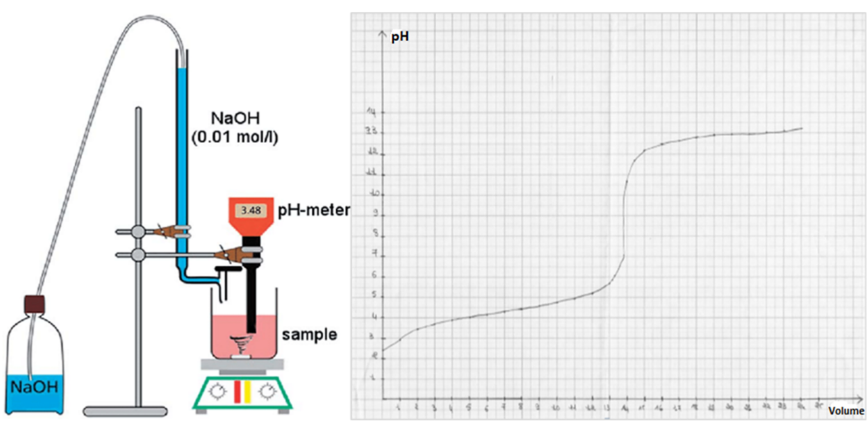

Figure 3. Traditional experimental setup.

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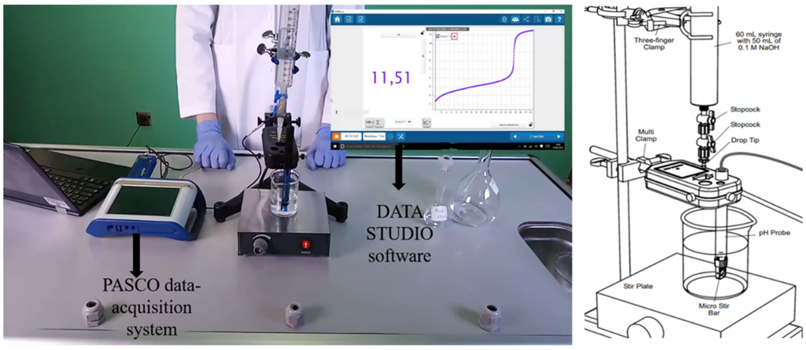

Figure 4. MBL experimental setup.

Table 1. Questions of the Assessment

1. Using your knowledge, propose a protocol to determine, by pH meter, the acetic acid present in V = 10 mL of vinegar diluted 10 times.
2. Use the method of tangents to determine the volume at the equivalence.
3. Write the chemical equation for the reaction between acetic acid and hydroxide ions.
4. What is the relationship between the amount of substance of the titrant and analyte?
5. Calculate the amount of substance of the titrant and analyte at the equivalence point.
6. Calculate the concentration of the analyte.
7. Deduce the quantity of acetic acid n in 100 mL of commercial vinegar.
8. Calculate the mass m of acetic acid in 100 mL of vinegar.
9. Calculate the degree of acidity of the vinegar and compare it with the commercial data.
10. Analyze and interpret the results.

Table 2. Achievement Rate of Students in Written Examination Items

question	skills tested in question	right answer	wrong answer	no answer
1	ability to identify the titrant and the analyte	78% (EG)	22% (EG)	0% (EG)
		64% (CG)	36% (CG)	0% (CG)
2	ability to draw the tangent to identify the equivalence point	98% (EG)	2% (EG)	0% (EG)
		76% (CG)	18% (CG)	6% (CG)
3	ability to write balanced full and ionic equations, including state symbol for the chemical reaction	86% (EG)	14% (EG)	0% (EG)
		70% (CG)	18% (CG)	12% (CG)
4	ability to calculate the amount of substance of the titrant and analyte at the equivalence point	92% (EG)	8% (EG)	0% (EG)
		70% (CG)	16% (CG)	14% (CG)
5	ability to calculate the concentration of the analyte in a dilute solution	76% (EG)	22% (EG)	2% (EG)
		32% (CG)	42% (CG)	26% (CG)
6	ability to use the dilution ratio to calculate the initial concentration of the analyte	64% (EG)	10% (EG)	16% (EG)
		22% (CG)	38% (CG)	40% (CG)
7	ability to calculate the mass concentration and determination of the acid degree of white vinegar	58% (EG)	28% (EG)	14% (EG)
		0% (CG)	20% (CG)	80% (CG)
8	ability to make a judgment and reach conclusions	74% (EG)	20% (EG)	6% (EG)
		0% (CG)	0% (CG)	100% (CG)

reason quantitatively and solve problems in a quantitative context. For the rest of the test, the experimental group did better in the questions that required analytical reasoning, especially the ability to make a judgment and reach conclusions. On the other hand, the control group had some difficulty relating the titration curve to the reactions of the molecules in the solution.

An independent sample t test was performed to see the impact of the use of MBL on students' performances in the test. A t test is a type of inferential statistic used to determine whether there is a significant difference between the means of two groups, in our case, the experimental and control groups.[61−63] The independent variable for this test is the procedure (lecture and traditional titration or MBL session) and the dependent variable is the exam score (maximum exam score was 20/20). The results are provided in Table 3. The

Table 3. Results of the Experimental and Control Group

groups	N	mean (M)	standard deviation
control	50	6.75	4.299
experimental	50	13.87	6.0259

experimental group (N = 50) was associated with an M = 13.68 (SD = 6.0259). In contrast, the control group (N = 50) had a numerically lower exam score of M = 6.75 (SD = 4.299). The null hypothesis of this study, H0 is that there is no difference between the experimental and control group vs H1, that differences will be observed (i.e., the experimental group did score better).

The results of the analysis indicate that the p value equals 9.41855.10−10 ($p(x \leq T)$ = 4.70927.10−10). It means that the chance of rejecting a correct H0 is slight: 9.419.10−10. The smaller the p value, the more it supports H1. Since the p value < α, H0 is rejected. The population means of the control group is considered not equal to the population mean of the experimental group. In other words, the difference between the means of the control group and experimental group populations is large enough to be statistically significant. On the basis of the obtained results, it appears that the students in the experimental group, who were required to attend a hands-on session using a microcomputer-based laboratory, performed better on the test than the control group.

After the MBL session, we asked students about the potential value of using the MBL, plus the nature of the learning occurring while working with the MBL. Most students reported that the absence of a delay between the event and its graphic representation helped them understand neutralization. In addition, the rapid increase in pH and inflection of the

https://doi.org/10.1021/acs.jchemed.1c01254
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titration curve at the equivalence point is difficult to follow quickly or continuously manually. As for the nature of the learning occurring, they said that since the MBL reduces experimental procedures, more time is available to understand the reactions in solution and acid−base titration in general. Finally, they mentioned that working with the MBL kept them interested and motivated during the session.

The research results showed that students who participated in a hands-on session using MBL performed better on the test; we realized that the experimental group could use scientific practices to explain phenomena during the hands-on sessions. In addition, we noticed a positive impact on students' competence to use resources (concepts, methods, techniques, and attitudes) when using the MBL. Furthermore, we could see that using the MBL motivates the students because they have much more time to observe and discuss the manipulation. We also found that the students' wrong answers in the control group mostly fell into the category of making judgments and reaching conclusions. This finding indicates that some traditionally taught students have difficulty understanding neutralization and related concepts.

■ CONCLUSION

The purpose of this article was to address whether the implementation of MBL in an academic situation can support knowledge acquisition and skill development. We conclude that it is not enough to allow students to manipulate the laboratory to claim that experimental work is advantageous to science learning. It is necessary to rethink the methods used for more effective integration of experimental work in the university environment and the conditions to ensure that students give meaning to the experimental activities they carry out. However, it is essential to develop their autonomy, insist more on group work, and improve their cognitive skills (observing, comparing, hypothesizing, reasoning, problem solving, decision making). Moreover, we believe that the effects of MBL enable innovation in science learning by modernizing and reorganizing laboratories, reducing time spent in the lab through faster measurements. Moreover, the computer can provide some form of guidance to the student, giving the instructor a little more latitude to, for example, solve learning challenges, rather than using the vast majority of their time solving technical problems.

Another important finding is that this study is vital to UCA because it solves a daily problem in teaching chemistry in laboratories. This developed technology enables the scheduling of hands-on sessions for more students in less time and with better results, thus increasing students' performance and teachers' efficiency.

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Notes

The authors declare no competing financial interest.

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https://doi.org/10.1021/acs.jchemed.1c01254
J. Chem. Educ. 2022, 99, 2548−2555