JOURNAL OF CHEMICAL EDUCATION
Article
pubs.acs.org/jchemeduc

The Effect of Procedural Guidance on Students' Skill Enhancement in a Virtual Chemistry Laboratory

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ABSTRACT: Various cognitive aids (such as change of color, arrows, etc.) are provided in virtual environments to assist users in task realization. These aids increase users' performance but lead to reduced learning because there is less cognitive load on the users. In this paper we present a new concept of procedural guidance in which textual information regarding the procedure of a task is provided to users. The users convert this information into physical actions to complete the task, which enhances their learning by creating a consolidated mental model. We use Multimodal Virtual Chemistry Laboratory, where students simulate a chemistry experiment with the help of procedural guidance. Evaluations reveal that the proposed guidance enhances students' learning and consequently increases their performance in real-world situations.

KEYWORDS: *High School/Introductory Chemistry, Computer-Based Learning, Inquiry-Based/Discovery Learning, Laboratory Instruction, Distance Learning/Self Instruction, Multimedia-Based Learning*

INTRODUCTION

Chemistry experiments are among the difficult tasks to be performed by students in laboratories. In real-world chemistry laboratories, students learn the performance of an experiment through various methods. For example, a teacher may perform the experiment and the students learn it by observing. Similarly, students may be briefed about an experiment using laboratory manuals and charts. The cognitive, affective, and psychomotor domains must be included for significant learning to occur.[1] In the real world, cognitive and motor skills can be better learned under the supervision of a trainer, but this is difficult because of cost and nonavailability of equipment.[2] In the context of these problems, many researchers have proposed different approaches for the teaching of chemical education, particularly at the high school level.[3] Virtual environments (VEs) can be of vital importance for learning and training activities.[2] VEs become more beneficial if they provide cognitive guidance to users during task performance.[2,4] The guidance may use various modalities such as audio, visual, or haptic.[5,6] The guidance is very useful, as it renders important information in a very simple way to carry out the task and hence increase user performance. However, excessive use of cognitive guidance in VEs decreases the users' learning and knowledge transfer in real-world environments because of their increased reliance on the training system.[4] In this paper, we present a concept of procedural guidance that will help students to carry out an experiment in a virtual chemistry laboratory in the correct manner while demonstrating high performance and improved learning. As the name depicts, the procedural guidance provides guidance to students regarding the procedure of an experiment.

RELATED WORK

The literature on virtual chemistry laboratories, including both two-dimensional (2D) and three-dimensional (3D) environments, is presented in this section. Similarly, the role and importance of cognitive guidance in virtual learning environments is also elaborated in the second part of this section.

Virtual Chemistry Laboratories

A virtual analytical system presented by Waller and Foster[7] allows students to learn the use of the spectrometer in laboratory. The system is beneficial to use for learning purposes but is limited to a single task. In order to deal with the problem of lack of equipment in laboratories, Tüysüz[8] developed a 2D virtual environment for high school students to learn chemistry. The evaluation revealed that the virtual laboratory had positive effects on students' learning. Another important work is that of Model ChemLab,[9] where students can simulate some chemical reactions. In addition, it permits students to learn the use of different apparatuses and chemicals, on which basis this system can be termed as very useful for students' learning. The environment of Model ChemLab is 2D, where the selection of an experiment, its apparatus, and its chemicals and their required amounts is carried out through menus and dialogue boxes, due to which the interaction becomes difficult as well as less realistic.

VLab is a collaborative virtual environment for chemistry education where students sitting on separate computers can collaboratively select chemicals and apparatuses for an experiment. In VLab, a simple chat window is used for collaboration among students. VLab can be used by students to improve their learning regarding some experiments, but the environment is less realistic because of its 2D nature.[10] The Virtual Unit Operational Laboratory (VUOL) is a 2D virtual environment that permits students to learn the control and operation of various kinds of industrial equipment using different interfaces such as a double-pipe heat exchanger interface, a gas absorber interface, and a cooling tower interface.[11]

Video recording materials have also been used for learning purposes by McKelvy,[12]but here the students remain passive.

Received: December 4, 2015
Revised: October 19, 2016

DOI: 10.1021/acs.jchemed.5b00969
J. Chem. Educ. XXXX, XXX, XXX−XXX

The Virtual Reality Undergraduate Projects Laboratory (VRUPL) is a 3D virtual chemistry environment developed for the training of undergraduate students.[13] VRUPL enables students to learn what apparatuses will be used and what will be their proper assembly in a particular experiment. In addition, students are guided about how to take various safety measures while working in real chemistry laboratories in both industrial and educational settings. Although the environment is helpful for learning safety principles, it does not allow the simulation of chemical reactions.

A fully immersive virtual environment based on CAVE technology was developed by Limniou et al.[14] where students can simulate the reaction of two chemicals. In addition, it allows the 3D visualization of molecules of the resultant product. The system was better for learning chemistry, but because CAVE is an expensive technology, its widespread use at the school level is difficult.

In Virtual Reality Accidents Laboratory, students can learn safety measures in order to avoid accidents in setting up real laboratories.[15] Although the virtual laboratory reported in ref 16 allows students to learn the procedure of an experiment and the assembly of the different glassware or apparatus required, it does not provide simulations of chemical reactions. The Virtual Reality Interactive Learning Environment (ViRILE) allows users to know various components of a chemical plant and the procedure of its operation for a chemical reaction by simulating an experiment reaction in it.[17] The evaluation of Virtual ChemLab revealed that students who used Virtual ChemLab had better exam scores and problem-solving capability.[18,19] An online virtual chemistry laboratory system was developed by Oxford University (Oxford, U.K.) to harmonize their first-year undergraduate teaching. This system contains a number of chemical reaction experiments in the form of video clips. The user can view the video clips by selecting two reactants and can repeat a particular reaction. The system was also suitable for users to learn about the safety rules during the experiments in the real laboratory but was much less interactive because of the video clips.[20]

In 2004, d'Ham et al.[21] presented a virtual chemistry lab for distance education where students enter the required data for an experiment using a web or remote interface, on the basis of which a robot then carries out the experiment. The online collaborative virtual classroom of Shudayfat and Bogdan[22] contains a periodic table through which students can collaboratively interact using their humanoid avatars and study the properties of an element including the visualization of its atomic structure in 3D. For collaboration among students, chat or voiceover is used.

Belletti et al.[23] used LabVIEW software to develop a virtual environment where students can learn the method of measuring the vapor pressure of a liquid using an isonteniscope. In 2007, Stone[24] reported that virtual laboratories using GC and HPLC simulators can play an important role in the teaching of virtual chromatographic exercises. According to his evaluation, both simulators were useful to guide the students about the chromatography in chemistry education. Late Nite Labs (LNL) is an online virtual chemistry lab for high school- and college-level chemistry education.[25] It is very useful for the improvement of learning. Interaction with the environment is mainly carried out through 2D graphical interfaces. Similarly, the iVirtualWorld[26] is a web-based environment where various 3D objects required for an experiment are selected from 2D menus using traditional mouse-based interaction. Similarly, different properties of the selected object are also set using a 2D graphical user interface (GUI), which makes the environment less realistic, and hence, it becomes difficult to achieve more immersion of the user.

In 2014, Winkelmann et al.[27] developed the Second Life (SL) virtual chemistry laboratory, where a small group of high school students perform an experiment both in SL and in real world. The survey demonstrated that the quality of students' results and lab report marks were similar in both the virtual and real-world labs. They found that virtual experiments took significantly less time to complete. They also found that virtual experiments are useful for distance education and feasible for students to perform the experiments themselves.

In real-world laboratories, students normally carry out the practical tasks according to their teacher's instruction, and without the teacher it is very difficult for them to perform an experiment. Therefore, in a virtual learning environment it is also necessary to provide some guidance where students take interest and perform their task more easily. However, these existing virtual laboratories have several limitations. For example, some environments contain only videos of the selected experiments where users have no control; some of them are 2D, which lacks realism and hence provides low immersion; and some are 3D environments but provide interaction with objects through menus and control boxes, making them less realistic. In addition, none of the existing virtual laboratories have used procedural guidance.

Guidance in Virtual Learning Environments

In order to learn procedural tasks, various methods are used, such as watching videos, reading instruction manuals/books, or listening to an expert person, but a majority of the researchers agree that practical repetition is very essential for learning step-by-step tasks.[2] To improve trainees' performance as well as learning skill, nowadays one of the important technologies is virtual reality, which permits trainees to interact with and physically manipulate the synthetic objects within a virtual environment.[2,28] To easily perform a complex task in a virtual environment, different types of cognitive guidance such as visual, aural, and haptic are provided to users.[30]

Chittaro and Venkataraman[29] presented a virtual environment that contains multifloor virtual buildings and uses two types of maps (2D and 3D) for users to search the estimation of direction for getting to the target. Nguyen et al.[5] utilized three types of navigational aids (compass, arrows, and lighting source) to help trainees in searching for the desired targets in a virtual environment. The guiding arrows and compass aids were found to result in better performance than the light source for reaching the target. Similarly, tracers and arrows were used as navigational guidance by Chen and Ismail[30] in their virtual environment developed for new car drivers to learn traffic regulations and signals. The authors compared guided and nonguided VEs and found that the use of guidance in VEs provides significant learning effects. Verbal alone and verbal plus mouse pointing can also be used by a trainer to guide the trainee in performing a particular task in a 3D virtual environment.[31] This method always requires the presence of a human expert and will be less useful when there is more than one trainee performing the task at the same time. Visual guides like change of color, pointing arrows, etc. can be used to indicate which object to select and where and how to place it in 3D virtual environments for assembly tasks. Similarly, haptic aids that attract the user toward the target location after an

DOI: 10.1021/acs.jchemed.5b00969
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object is selected have also been found to be useful in such environments.[28]

Rodriguez et al.[2] compared the effects of indirect aids (books, manuals, etc.) and direct aids (arrows, change of color, etc.) on user performance, learning, and knowledge transfer to the real world using a 3D virtual assembly environment. They reported that direct aids increase performance but affect knowledge transfer because there is less cognitive load on the user. If direct aids are carefully used with semantic aids, this will increase not only user performance but also user learning and knowledge transfer to the real world.[32]

In order to help students carry out an experiment in the correct manner with high performance and improved learning in a virtual chemistry laboratory, we propose the concept of procedural guidance. This guidance assists students regarding the procedure of an experiment. To analyze the effect of procedural guidance on students' learning and task performance, we developed a 3D virtual chemistry laboratory where the students simulated an experiment (standardization of sodium hydroxide) using two experimental conditions: (1) with procedural guidance and (2) without procedural guidance. We also investigated the effect of procedural guidance on students' performance in the real lab.

MULTIMODAL VIRTUAL CHEMISTRY LABORATORY

In this section we present the concept of procedural guidance and its use and effectiveness in virtual environments designed for learning or education purposes. This guidance is actually the textual information displayed to students in a real-time step-by-step manner describing the procedure or actions required to perform a task (a chemistry experiment in our case).

The students would convert the guidance into physical actions in order to perform the experiment. Our hypothesis was that this guidance would not only allow students to perform an experiment without teacher involvement but would also enhance their learning and task performance. In order to investigate the validity of our hypothesis, we developed a Multimodal Virtual Chemistry Laboratory (MMVCL), where students can simulate their chemistry experiments using the procedural guidance. MMVCL provides some advantages over previous virtual chemistry laboratories:

1. Multimodal feedback provides detailed information about the physical and chemical properties of chemicals and apparatus. It allows users to enhance their learning about the theory of chemicals/objects.
2. Step-by-step procedural guidance is provided to students while they perform an experiment in MMVCL.
3. Procedural guidance enables students to easily carry out an experiment in MMVCL without taking help from the teacher.

MMVCL is a 3D virtual environment like a real chemistry room/lab, as shown in Figure 1. The basic glassware, chemicals, and apparatus required in the high school- and intermediate (higher secondary school)-level experiments are available in MMVCL. These chemicals and glassware have been put in their corresponding shelves as shown in Figure 1. Like real-world chemistry laboratories, MMVCL also has a table in the center where some of the apparatus, such as a digital balance, spirit lamp, and buret, have been placed permanently. To carry out an experiment, a student can select and bring a chemical or glassware to the table using Nintendo Wiimote,[33] which provides a realistic interaction and more user freedom.

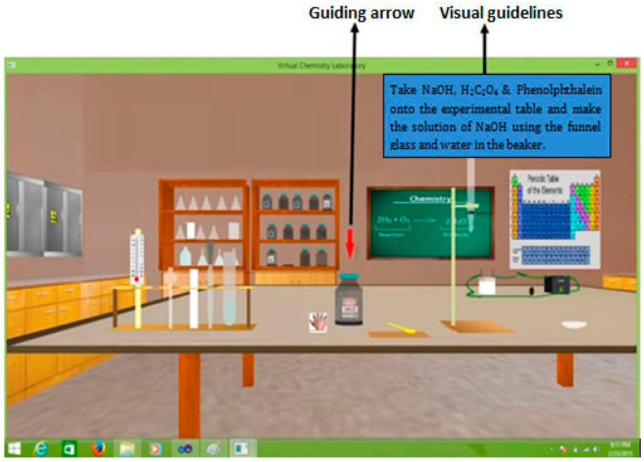

Figure 1. Inside scenario of MMVCL.

In any 3D virtual environment, selection and manipulation are considered the most important tasks. The selection of an object is done before it is manipulated. The necessary condition for an object's selection in MMVCL is collision. This means that whenever the virtual hand collides with an object, the latter becomes selectable. To validate the object's selection, the user needs to press button "A" of the Wiimote, after which it is manipulation is done. The system performs different actions when the collision occurs. If the virtual hand collides with an object, the audio/visual information related to the object is provided by the system or the object is selected. If a selected object collides with any other object in the environment, the former stops moving further. In a virtual environment an object needs realistic collision response with other objects to show solidity.[34]

Experiment Selection

MMVCL contains a list of experiments (as shown in Figure 2) from which a user can select the one to be performed. After the selection, step-by-step procedural guidance is provided.

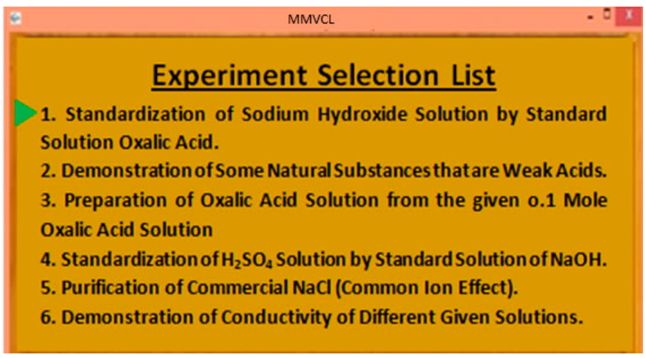

Figure 2. Experiment selection list in MMVCL.

Procedural Guidance

The procedural guidance actually consists of textual instructions displayed on the screen to guide the student what to do, for example, what chemical to use, what glassware to use, and in which sequence or order. The student follows these instructions while performing the experiments (as shown in Figure 1). In addition, MMVCL tracks the user's actions, and

DOI: 10.1021/acs.jchemed.5b00969
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once it detects that the student has completed all of the instructions in the current step, then the instructions regarding the next step are displayed, and so on. In this way the student can complete the experiment independently without taking guidance from the teacher or textbook.

In order to explain the concept of procedural guidance, we take an example of simulating an experiment in MMVCL. When the experiment “Standardization of Sodium Hydroxide Solution by Standard Solution of Oxalic Acid” is selected from the list of experiments, the instructions shown in Figure 3 are

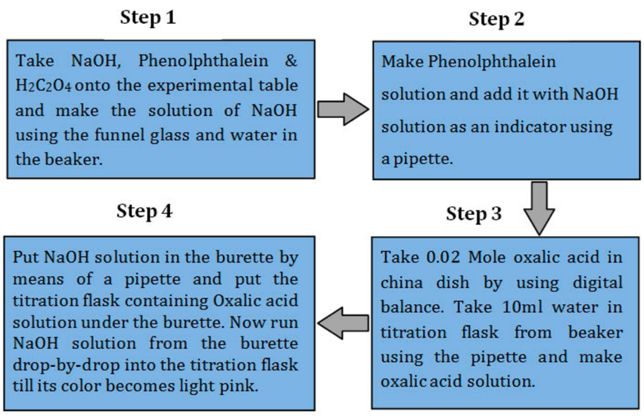

Figure 3. Step-by-step guidance.

displayed in a step-by-step manner. Here in the first step, the student is instructed to bring NaOH, $H_2C_2O_4$, and phenolphthalein onto the table and then to make the NaOH solution using the funnel glass and water in the beaker. After the student has read and understood these instructions, the next task for the student is to convert them into physical actions, i.e., search for and bring the stated chemicals. To search for the required chemicals, the student has to navigate toward the cupboard where they have been placed.

Once the student comes near the cupboard, the labels on each bottle are clearly visible and readable, which enables the required chemicals to be identified. Further, upon touching the bottle of the desired chemical, the student is given more information such as its name, formula, function, physical/chemical properties, etc. in both audio and visual form. The distinction of MMVCL is that it not only provides guidance regarding the procedure of a chemical experiment but also strengthens the students’ concept on theoretical side through multimodal feedback. It is also worth mentioning that the provision of step-by-step procedural guidance and multimodal information is done in real time and given when and where it is required.

The schematic shown in Figure 4 elaborates the working mechanism of procedural guidance where a set of instructions is provided to students/users in each step. The system continuously monitors the student’s task performance; if instructions given in the first step are completed successfully, then the next set of instructions is rendered, and so on. The amount of procedural guidance can be determined from the complexity of an experiment. For a simple experiment there are a few procedural steps, but for a long and complex experiment the number of steps increases. For a student it will be difficult to act upon the instructions given in a particular step of the procedural guidance if the student does not know the glassware or chemical required for completion of the given step. In order

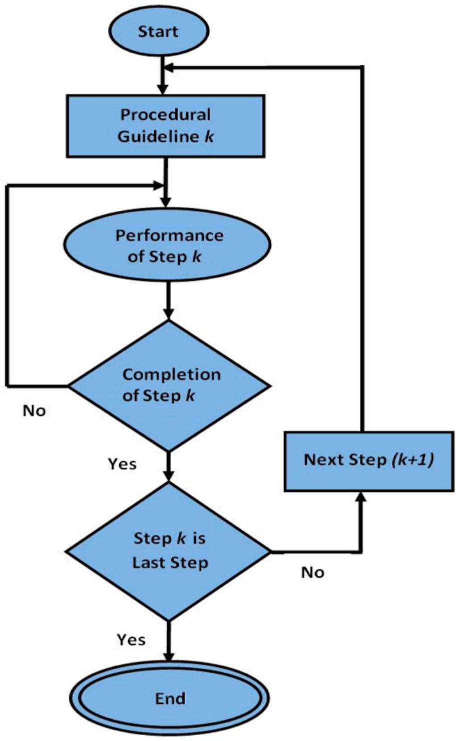

Figure 4. Stepwise provision of procedural guidance in MMVCL.

to solve this problem, we provide multimodal (textual and audio) feedback capability in MMVCL.

Multimodality

Whenever a student selects (virtual hand collides with) a chemical item or glassware, information about its name, properties, function, etc. is provided in audio or textual form, as shown in Figure 5. Here a bottle containing sodium

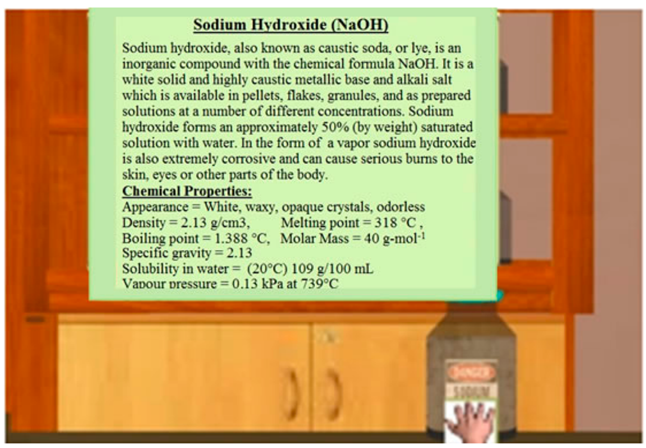

Figure 5. Textual information in MMVCL.

hydroxide has been selected using the virtual hand, and the textual information has been displayed over the bottle. The displayed text contains a number of important points about sodium hydroxide such as its state, common name (caustic soda or lye), formula (NaOH), color, density, melting and boiling points, specific gravity, and solubility in water. In addition, it has also been shown that it occurs in the inorganic group and is an alkali salt. The textual information about a selected object (chemical or glassware) remains on display until the object is

DOI: 10.1021/acs.jchemed.5b00969
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released. The same information is provided to students in audio form as well. This information is very useful for students' learning enhancement. The multimodality permits students to get detailed information about the chemical objects, which improves their learning. The multimodal feedback also works as cognitive aid for users while performing an experiment. For example, in an experiment that requires the preparation of two solutions from two different chemicals, if the student prepares the two solutions but meanwhile forgets which solution contains which chemical, the student can be told this through multimodal feedback simply by touching the container of the solution with the virtual hand.

■ EXPERIMENTS AND EVALUATIONS

Experimental Setup

For the development of MMVCL, we used Visual Studio 2010 with OpenGL, installed on a Core i3 Laptop having a 2.4 GHz processor, 2 GB of RAM, and an Intel HD graphics card. For interaction we used Nintendo Wiimote. Similarly, a 40 in. LED screen was used for display during experiments.

Experimental Protocol and Task Description

Fifty-seven students (high school and higher secondary level; 50 male, seven female) participated in the evaluations. Twenty-six participants were taken from a higher secondary school (i.e., college), while the remaining 31 were taken from three different high schools. They had ages ranging from 16 to 19 years. A university-level assistant professor in chemistry remained present during the whole evaluation process for expert opinion. These students were divided into three groups (i.e., G1, G2, and G3) containing equal numbers of students. There were two females in G1, two in G2, and three in G3. The students in G1 and G2 were briefed with the help of a 30 minute demonstration in which they were taught about navigation, selection, and manipulation of objects in MMVCL. We selected one of the complex experiments (standardization of sodium hydroxide solution by standard solution of oxalic acid), which is included in both the high school and higher secondary levels and also contains multiple steps. The students in G1 then performed the selected experiment in MMVCL without procedural guidance, but they studied/consulted the practical notebook (which contains descriptions of the chemicals and apparatus to be used in a particular experiment as well as its procedure) for guidance. The students in G2 performed this experiment with the help of procedural guidance. It is worth mentioning that multimodal feedback was equally available to both groups while they were performing the experiment. Here we recorded the task completion time and errors for each student in both groups (G1 and G2). Each participant filled out a questionnaire after completion of the experiment in MMVCL. The students in G3 were guided by their teacher using the traditional method, where they used the practical notebook/worksheet and white board in a real lab setup. Then these three groups G1, G2, and G3 were taken to a real chemistry laboratory where they performed the same experiment. The task completion time and errors were recorded for each student. The subjective responses of students regarding the easiness of the procedural guidance and its effect on the students' performance in MMVCL and real lab performance were collected through a questionnaire. The students answered each question on a scale of five options.

■ RESULTS AND DISCUSSION

In this section we present the analysis of the data recorded/collected during the experiments.

Subjective Measure of Procedural Guidance in MMVCL

In the first part of the analysis, data were gathered from the students of G2 using a questionnaire when they completed the experiment in MMVCL with the help of procedural guidance. The questionnaire contained the following questions.

1. The step-by-step procedural guidelines in the MMVCL are easy to understand?
2. The experiment can be easily performed in MMVCL by reading the step-by-step procedural guidelines and converting them into physical actions?
3. The step-by-step procedural guidelines help to perform the experiments in the MMVCL without a teacher?
4. After performing the experiment in the MMVCL using step-by-step procedural guidelines, I feel confident and can easily perform the experiment in the real lab?
5. Overall, I am satisfied with the step-by-step procedural guidelines in MMVCL?

For the first question, which is related to the easiness of understanding the procedural guidance, 52.6% of the students selected the "Easier" option and 36.9% of the students selected the "Easiest" option (see Figure 6). It can be concluded that it is very easy to understand the procedural guidance to perform the experiment according to its procedure. For the second question, which is related to performance of the experiment using the procedural guidance, 57.9% of the students selected the "Easier" option, and 36.3% of the students selected the "Easiest" option (see Figure 7). This means that the students understood the procedural guidance and converted it into physical actions required for the performance of the experiment in MMVCL.

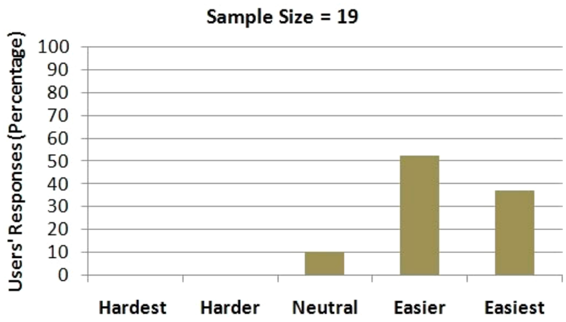

Figure 6. Easiness of procedural guidance.

Similarly, 58.1% and 29% of the students selected "Agree" and "Strongly agree", respectively, for the third question. In addition, 61.3% of the students selected the "Agree" option and 32.2% of the students selected the "Strongly agree" option for the fourth question (see Figure 8). The last question, regarding the students' satisfaction from the procedural guidance, got the vote of 57.9% and 42.1% of the students for the "Higher" and "Highest" options, respectively, as shown in Figure 9.

Performance Measure of Procedural Guidance in MMVCL

The second part of the analysis was to check the performance of both groups (G1 and G2) in performing the same experiment in MMVCL using their respective experimental

DOI: 10.1021/acs.jchemed.5b00969
J. Chem. Educ. XXXX, XXX, XXX−XXX

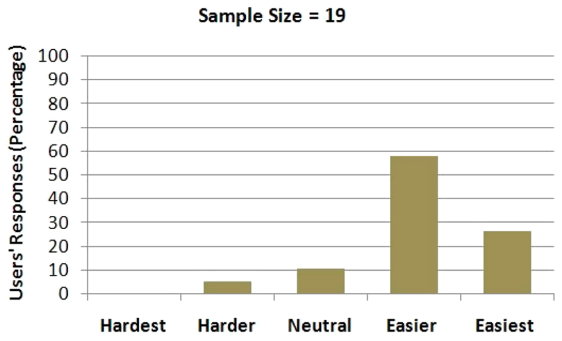

Figure 7. Experiments performance in MMVCL using procedural guidance.

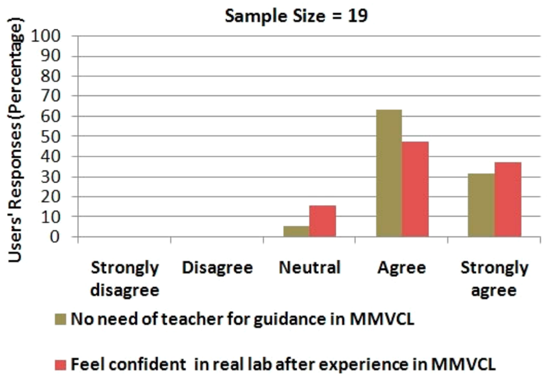

Figure 8. Effectiveness of the procedural guidance in MMVCL and students' confidence in the real lab.

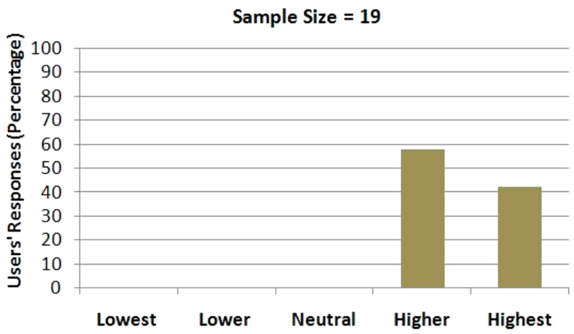

Figure 9. User satisfaction from MMVCL.

conditions. The experimental conditions were the following for the groups:

1. G1 performed the experiment in MMVCL without procedural guidance.
2. G2 performed the experiment in MMVCL using procedural guidance.

As stated earlier, multimodal feedback was equally available to both groups (i.e., G1 and G2). The data recorded in this section consist of their task completion times and the mean of errors that occurred during task execution.

Task Completion Time. The analysis of variance (ANOVA) for task completion time is significant ($F(1, 37) = 22.24$, $P < 0.05$). The average task completion time and standard deviation for each group are given in Table 1. Comparing the task completion time of G1 with that of G2, we obtained a considerable difference, which means that students who got experience in MMVCL and used procedural guidance

Table 1. Comparison of Performance Measures by Procedural Guidance Status in a Virtual Lab Setting

Group and Procedural Guidance Status	Task Completion Time (min)[a]		Number of Errors in Task Execution[a]	
	Mean	Standard Deviation	Mean	Standard Deviation
G1 (N = 19), without guidance	25.02	2.56	4.78	1.03
G2 (N = 19), with guidance	20.52	3.27	2.63	0.76

[a]The Multimodal Virtual Chemistry Laboratory (MMVCL) experiment evaluated was the standardization of sodium hydroxide solution by a standard solution of oxalic acid.

were far better compared with those who did not use procedural guidance in MMVCL.

Number of Errors during Task Execution. Invalid or unnecessary actions of users were considered as errors, which were counted for each user as the experiment was performed. This includes the selection of a wrong chemical or apparatus, its invalid use, and wrong navigation. We observe that G2 had considerably fewer errors than G1. The mean and standard deviation of errors in task execution for each group are given in Table 1.

Performance Measure of Procedural Guidance in the Real Lab

The objective of the third part of analysis was to investigate the performance of all three groups (G1, G2, and G3) while performing the experiment in the real chemistry laboratory. The students' performance was measured in terms of task completion time and errors.

Task Completion Time. The analysis of variance (ANOVA) of task completion time for the three groups is significant ($F(2, 55) = 29.74$, $P < 0.05$). In multiple comparisons of G1 with G3 and G2 with G3, the ANOVAs ($F(1, 37) = 41.19$, $P < 0.05$ and $F(1, 37) = 49.51$, $P < 0.05$, respectively) were found to be significant, while the ANOVA of G1 and G2 was not significant. The mean and standard deviation of the task completion time for each group are given in Table 2. Comparing the task completion times of G1 and G2

Table 2. Comparison of Performance Measures by Procedural Guidance Status in a Real-Life Lab Setting

Groups and Procedural Guidance/MMVCL Status	Task Completion Time (min)[a]		Number of Errors in Task Execution[a]	
	Mean	Standard Deviation	Mean	Standard Deviation
G1 (N = 19), MMVCL without guidance	19.17	2.06	2.31	0.74
G2 (N = 19), MMVCL with guidance	19.02	2.00	2.10	0.73
G3 (N = 19), no MMVCL	23.67	2.25	3.57	1.46

[a]The Multimodal Virtual Chemistry Laboratory (MMVCL) experiment evaluated was the standardization of sodium hydroxide solution by a standard solution of oxalic acid.

with that of G3, we obtained a considerable difference, which means that students who got experience in MMVCL were far better than those who did not use MMVCL. Much less difference between G1 and G2 in the real lab was observed, as shown in Table 2, because both groups got experience in MMVCL. The effectiveness of procedural guidance can be concluded from the performance comparison of G1 and G2 in

DOI: 10.1021/acs.jchemed.5b00969
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MMVCL (performance in virtual environment), which is significant as shown in Table 1.

Number of Errors during Task Execution. Again, the invalid or unnecessary actions of users were considered as errors, which were counted for each user as the experiment was performed in the real lab. The ANOVA of errors for G1, G2, and G3 is significant ($F(2, 55) = 11.13$, $P < 0.05$). We observe that G1 and G2 had considerably lower numbers of errors compared with G3.There is also a difference between G1 and G2 in the real lab, but it is not significant. The effectiveness of procedural guidance can be concluded from the error comparison of G1 and G2 in MMVCL (performance in virtual environment), which is significant as shown in Table 1. Table 2 presents the mean of errors and standard deviation for each group in the real lab.

Measuring Students' Learning in MMVCL

In order to judge the individual learning of students, we asked different questions from the three groups such as identifying various chemicals, apparatuses, and their functions to perform the experiment in the real environment in the correct manner. Comparing G1 and G2 (the groups trained by MMVCL) and G3 (the group trained by the traditional method), we observed a considerable difference in their learning (see Figure 10). The following formula was utilized to measure the success of students:

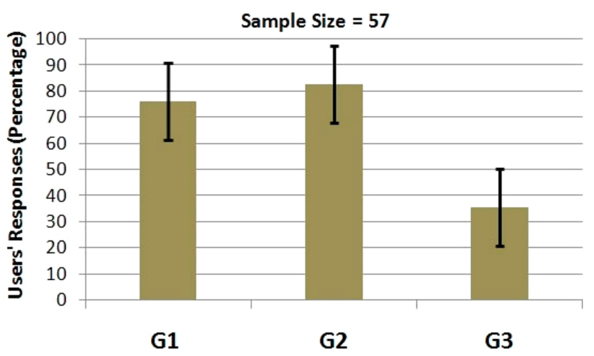

Figure 10. Mean success rates of G1, G2, and G3, with standard deviations shown as error bars.

$$\text{success rate} = \frac{\text{correct answers}}{\text{total questions asked}} \times 100\% \quad (1)$$

Here the mean success rates of G1 and G2 were 76.2% (SD = 8.2%) and 82.7% (SD = 11.5), respectively, while that of G3 was only 35.4% (SD = 10.7), as shown in Figure 10.

To summarize the above results, we can say that students were overall satisfied with various aspects of the procedural guidance such as the simplicity and understandability of the instructions, its conversion into physical actions, and experiment performance in MMVCL without the teacher's help. Similarly, we observed a significant difference between the performance of G2 (students who used procedural guidance) and G1 (students who did not use procedural guidance) when students performed the experiment in MMVCL. Although the performances of G1 and G2 in the real lab were almost the same, there was a considerable difference between the performance of G2 and G3 (students who were trained by the traditional method). Similarly, the learning (success rate) of students who used procedural guidance in MMVCL (G2) was significantly better compared with the learning of G3. On the other hand, it was found to be slightly better than that of the G1.

■ CONCLUSION

In this paper we have presented a new concept of procedural guidance in which textual information regarding the procedure of a task is provided to users. The users convert this information into physical actions to complete the task, which enhances their learning by creating a consolidated mental model. For evaluation, 57 students were divided into three equal groups called G1, G2, and G3. The students in G1 then simulated an experiment in Multimodal Virtual Chemistry Laboratory (MMVCL) without procedural guidance, while those in G2 simulated this experiment with the help of procedural guidance in MMVCL. The students in G3 were briefed by their teacher (traditional method) in a real chemistry lab using a practical book and white board. Then these three groups carried out the experiment in the real lab. The procedural guidance has been shown to enhance students' performance in a virtual lab exercise, and exposure to a virtual lab experience results in better performance in a traditional laboratory setting.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are thankful to all of the institutes who participated in this evaluation. We thank Confidence Institutes of Science & Technology, Chakdara Public School, Alhuda Girls Model School, and Faran Public School Dir (L). We are also thankful to Department of Chemistry of the University of Malakand for providing some of the chemicals and apparatuses for these experiments. We are especially thankful to Dr. Ezzat Khan (Assistant Professor, Department of Chemistry, University of Malakand), who remained with us during the evaluation process.

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DOI: 10.1021/acs.jchemed.5b00969
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