





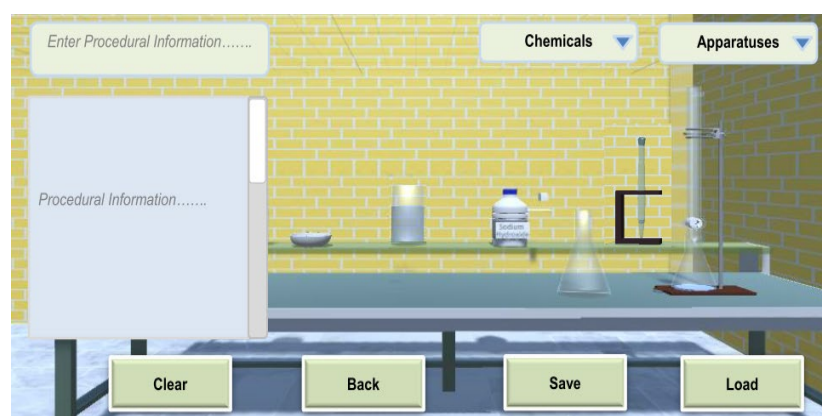
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# A Subjective Study on the Effects of Dynamic Virtual Chemistry Laboratory in a Secondary School Education

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Virtual chemistry laboratories (VCLs) are the alternative solutions of the physical laboratories, where students can virtually conduct their experiments with a lower cost, and in an efficient and safer way. Considering the importance of technology-enhanced learning and that of the experimental study, several VCLs have been proposed. However, the existing VCLs are static and only provide the simulation of pre-defined experiments, procedures, or safety procedures and cannot be adapted according to the students' level or new experimental tasks. In this paper, we proposed a dynamic virtual chemistry lab (DVCL) where instructors or experts are allowed to add a new chemical experiment by adding its apparatus, chemicals, glassware, and mechanism or add something new to its properties. We conducted a subjective study with field experts to investigate the effect of proposed DVCL in secondary school chemistry education. During evaluation, twenty-seven field experts were participated and evaluated the proposed DVCL with system usability scale (SUS)-questionnaire and by a simple questionnaire. The results showed that the proposed DVCL is very helpful for students' performance and mental modeling and also for effortlessly uplifting their knowledge for hands-on experiments.

## Graphical abstract



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## 1. Introduction

Interactive teaching plays a vital role in the creation of students' conceptual learning for hands-on activities, particularly in chemistry education [1,2]. Conducting hands-on

experiments are challenging tasks in the real chemistry laboratories, especially for the new students [2]. In this context, the use of virtual chemistry labs (VCLs) provides a

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state-of-the-art solution for problems in chemistry education where the students' performance can be improved for hands-on experiments by using virtual experiments. VCLs provide the predefined chemical experiments or reactions, including the sequence of steps and their procedures, to train the students for hands-on experiments accordingly [3]. In physical laboratories, the instructor may also assign to their students new experimental tasks according to their cognitive level. Before hands-on activities, it is necessary to guide the students about the assigned experimental tasks. In this context, VCL plays a vital role in the mental modeling of students for the new experimental tasks [2,3]. Therefore, a number of virtual learning environments (VLEs) have been developed in chemistry education including two-dimensional (2D) and three-dimensional (3D) to assist students in lab experiments.

A study has been conducted by Sevil [5] to compare static and dynamic representations of models of oxygen atom. In this study three animation-developing software were used i.e., ChemSense, K-Sketch and pencil for drawing oxygen atomic model and motion of electrons in orbitals around nucleus. Evaluation revealed that animation softwares are important tools in science classes and could help science educators in making of students' mental model. An online collaborative 3D virtual class room developed by Eman et al., [6] consist a periodic table in which users can interact collaboratively where they can also use humanoid avatars for collaborative communication and audio based aids. Students can study the visual information of a chemical element including properties and atomic structure in 3D visualization. Similarly, Valence Shell Electron Pair Repulsion (VSEPR) is an online virtual chemistry classroom developed by Kenney and Merchant [7] for 3D rendering of molecules and ions. A Virtual Science Lab (VSL) [8] is a web-based 2D platform where authors have claimed the simulation of different experiments of middle school level chemistry but have not provided explicit details. Robert and Piotr [9] have studied the effectiveness of using hand's gestures in 3D virtual chemistry lab. Similarly, Wu et al. [10] used hand gestures using leap motion to simulate titration based experiments in a 3D virtual chemistry lab and reported that the virtual reality chemistry lab could enhance and promote users' learning confidence under suitable learning intensities. The ChemCollective [11] is an online collection of virtual labs, scenario-based learning activities, tutorials, and concept tests. Labster [12] is an online 3D environment in which students can learn principles of atomic structures and can also simulate experiments for evaluating pH and pOH by mixing of different substances to achieve a certain pH level in acids and bases. Similarly, Oxford University England (OUE) has developed a system which renders video of a chemical reaction whenever a user combines (selects) two virtual chemicals [13]. The existing VCLs are efficient systems for familiarizing the learners with their lab works and can resolve the issues encounter by different centers of learning/institutions in lab activities. However, the existing VCLs are static and only provide the simulation of pre-defined experiments, procedures, or safety procedures and cannot be adapted according to the students' level or new experimental tasks [2]. Therefore, the development of a dynamic VCL that facilitates instructors or experts to include a new chemical experiment by adding its apparatus, chemicals, glassware, and mechanism.

In this paper, we proposed a dynamic virtual chemistry lab (DVCL) where instructors or experts are allowed to add a new chemical experiment by adding its apparatus, chemicals, glassware, and mechanism or add something new to its

properties. We conducted a subjective study with field experts to investigate the effect of proposed DVCL in secondary school chemistry education. During evaluation, twenty-seven field experts were participated and evaluated the proposed DVCL with system usability scale (SUS)-questionnaire [4] and by a simple questionnaire. The results showed that the proposed DVCL is very helpful for students' performance and mental modeling and also for effortlessly uplifting their knowledge for hands-on experiments.

## 2. Material and Methods

This section presents the proposed dynamic virtual chemistry laboratory (DVCL). DVCL provides a 3D virtual laboratory like a physical chemistry laboratory. A user can interact with virtual chemical items by using mouse and keyboard. In DVCL instructors or experts are allowed to add a new chemical experiment by adding its apparatus, chemicals, glassware, and mechanism or add something new to its properties. These chemicals and glassware would be chosen from their respective menus, as shown in Figure 1. DVCL provides the following advantages over previous VCLs:

- In DVCL, instructors or experts are allowed to add new experiments for secondary school-level chemistry experiments.
- Instructors may add apparatuses, chemicals, and glassware from the menu lists.
- Instructors are allowed to add mechanisms or procedural information in texts for guiding the students about the procedure of experiments.



Fig. 1. The inside scenario of DVCL.

The overall architecture of the proposed DVCL is shown in Figure 2. The principal components of the DVCL are described below:

### 2.1 User Interface for Interaction

In DVCL, for the addition of a new experiment, initially, a user is to select a required chemical or an apparatus from menus using a mouse. The chemical or an apparatus is directly mapped via the mouse cursor to calculate its 3D position for further interaction. Similarly, the keyboard is used for the addition of procedural textual information according to the procedure of the experiment(s).

### 2.2 Addition of New Experiments

In DVCL, chemistry teacher are allowed to add new experiments along with their relative apparatuses and chemicals. Students can learn the procedure of experiments such as assembly of various equipment (apparatuses and glassware) required in an experiment and their required amount of chemicals for reaction. In the current context of DVCL, no mechanism is provided for simulating chemical

reactions. However, by reading procedural information in DVCL, students can estimate the amount of chemicals needed for reactions. Therefore, they can perceive information about the required amount of chemicals for hand-on or physical experiments. The following are the main mechanisms for adding new experiments:

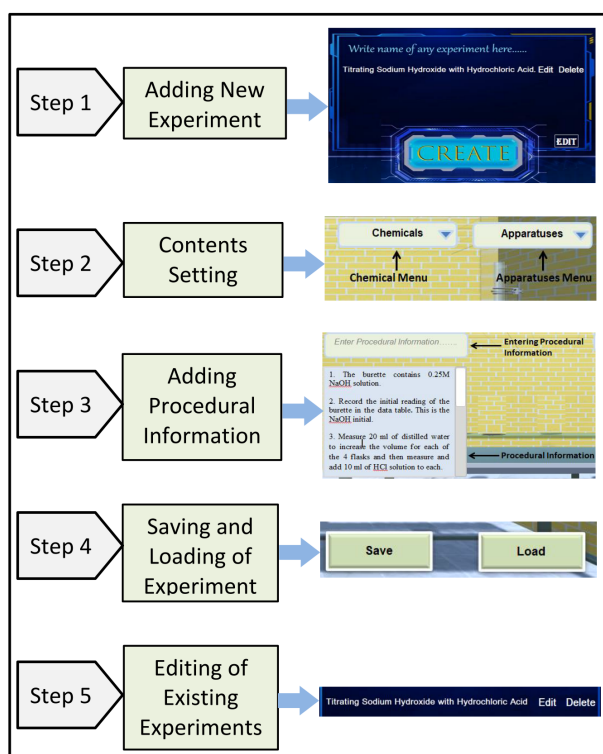


Fig. 2. Architecture model of the DVCL.

### 2.3 Contents Setting

In DVCL, the contents setting specify the contents, such as title of the experiment, chemicals, apparatuses, and glassware, for new experiments to be generated. In the first step, a teacher or expert would add the title of a new experiment (see Figure 3). After adding a title, the teacher or expert can now use menu lists (i.e., chemical and apparatus lists) to select the required chemicals, and apparatuses or glassware, as shown in Figure 4. A teacher can easily find the required items from menu lists, for instance, what chemicals to use and what apparatuses or glassware to use in the setting of a new experiment.

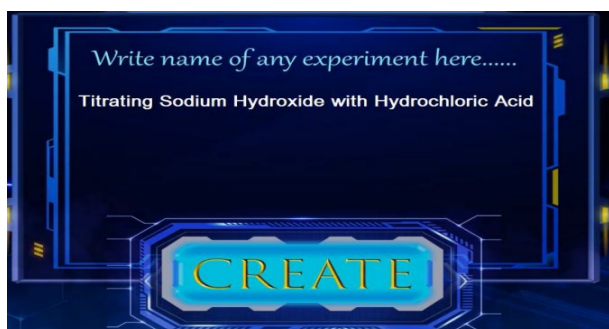


Fig. 3. Adding title of the new experiment in list.

To demonstrate the concept of contents setting technique, we take the example of a new experiment "Titrating Sodium Hydroxide with Hydrochloric Acid" for addition in the proposed

DVCL. The chemicals and glassware used in this experiment are sodium hydroxide, Hydrochloric acid, distilled water and etc in chemicals and burette, pipette, flask, beaker, burette clamps, china dish and etc in apparatuses or glassware. These chemical items and apparatuses or glassware are chosen from the item menu lists. After selection, these chemicals and apparatuses are displayed on the table in the environment. Users can now assemble the apparatuses and glassware according to the procedure of the experimental task. As mentioned above, in the proposed DVCL, no mechanism is provided for simulating chemical reactions. Therefore, users or students can perceive the chemical bottle consists of the labels, from which they can easily read and identify the required chemicals. In addition, students can also estimate the amounts of chemicals required for reactions by reading procedural information.



Fig. 4. Contents setting from menus.

### 2.4 Procedural Information

In DVCL, chemistry teacher can also add the procedure of new experiments. Procedural information are the cues of assisting the students to understand the contents (such as chemicals and glass wares) and their using in the experimental tasks according to the mechanism. Procedural information, actually consist of textual instructions, display on the screen to assist the student about each experimental step. Students can easily read these instructions to understand the actual mechanism of an experiment, for instance, how many steps are in the experiment, what to do, and what chemicals or glassware to use in the experimental steps. For adding step-by-step instructions, the teacher can use a text box about the new experiment. After adding step-by-step instructions, it would display in the box of procedural information as shown in Figure 5. During the experimental tasks, the students assemble various pieces of equipment by following step-by-step procedural information. As previously stated, in DVCL no mechanism is provided for simulating chemical reactions. However, students can estimate the amounts of chemicals required for reactions by reading procedural information. In such a manner, the students can learn the procedure of any experiment and consolidate their mentality for hands-on or physical experiments.

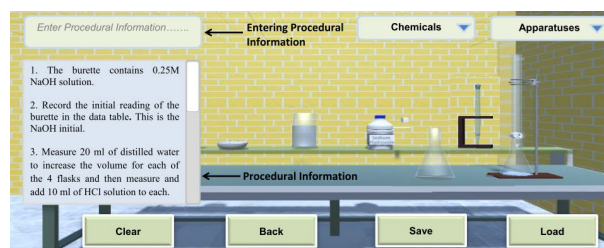


Fig. 5. The inside scenario of DVCL.

### 2.5 Saving and Loading of Experiments



Once the contents and procedural information for a new experiment have been successfully set, the experiment can be saved as a separate environment. The user or student can load the saved experiment from the experiment list. The user can perform assembly tasks and learn chemical estimation amounts, as well as procedural information.

### 2.5 Editing of Existing Experiments

After successfully saving an experiment in the DVCL, the experiment can also be changed by an instructor. Using the edit option, the instructor can make additional changes to the contents and procedural details from the experimental list.

## 3. Results and Discussion

This section presents the subjective assessment from the chemistry experts. The proposed system was evaluated by chemistry experts to know about the effect of the proposed DVCL in hands-on experiments. In this regard, we conducted a subjective study by interviewing the field experts.

### 3.1 Experimental Setup and Evaluation

The proposed system was implemented in MS Visual Studio with Unity 3D Engine 2021 version on Dell Corei7 laptop. For statistical analysis, SPSS (statistical package for social sciences) was used.

### 3.2 Experimental Protocol and Task Description

For evaluations, twenty-seven chemistry experts from different institutions, including secondary school, higher secondary school, and university-level chemistry teachers participated. They included both male and female teachers (21 males and 6 females). Before the evaluations, experts were contacted about the aim of the study

and requested for appointments in their office hours. The average duration of each evaluation with experts was 35 to 40 minutes. The evaluation process was consisted of four steps, the details of which are given below:

In the first step, we obtained all the background information about each teacher, such as their gender, their

prior education, their experiences and their working context in a generic sense. In the second step, we delivered a 15-minute demonstration about the basic function of the proposed DVCL. We briefed them on how to add new experiments, their contents and settings, and procedural information. In the third step, they performed different tasks, such as adding new experiments, their contents and settings and procedural information using their corresponding menu boxes in the proposed DVCL. In the last step, each of the field experts (teachers) evaluated the proposed DVCL with a system usability scale (SUS) questionnaire [4] and a simple questionnaire to find their personal feelings.

### 3.3 Subjective Analysis using System Usability Scale

In this phase, data were gathered from the field experts (both male and female experts) using system usability scale (SUS) questionnaire [4] and a simple questionnaire to find their personal feelings about the proposed DVCL. SUS gives a single value that represents the overall usability of the system. It uses ten statements (see Table 1) about the system usability. The field experts were to answer with numeric values from 1 to 5; where 1 indicates strongly disagree and 5 indicates strongly agree. In addition, another simple questionnaire also used containing five more general questions.

Table 1 summarizes the feedback of the participants using the ten statements of the SUS questionnaire [4]. The scale value is subtracted one from the score for statements that belong to an odd number, and five from the score for statements that belong to an even number. In Table 1, each row shows the feedback about one particular statement from all the twenty-seven participants. For example, in response to statement 1, twenty-two participants rated it as 5, and five students rated it as 4; therefore, the average score is calculated as:  $(((5 - 1) * 22) + ((4 - 1) * 5) / 27 = 3.81)$ . Similarly, in response to statement 2, twenty-three participants rated it as 1, and four participants rated it as 2, therefore the average value is calculated:  $(((5 - 1) * 23) + ((5 - 2) * 4) / 27 = 3.85)$ . Here, the value 47 represents the total number of participants, which is used for average calculation. In this manner, the total of the average scores was 37.40 and SUS score was  $37.40 * 2.5 = 93.51$ .

**Table 1.** Subjective results collected from 27 field experts using SUS questionnaire. The total of the average score is 37.4 and SUS score is  $37.4 * 2.5 = 93.51$ .

S.No	Concerned Statements	Strongly Disagree	2	3	4	Strongly Agree	Average Score
1	I think that I would like to use this system in secondary school chemistry education.	0	0	0	5	22	3.81
2	I found the system unnecessarily complex for students.	23	4	0	0	0	3.85
3	I think the system is easy to use.	0	0	1	3	23	3.85
4	I think that I would need the support of a technical user to be able to use this system.	20	5	2	0	0	3.66
5	I found the various functions in this system were well integrated.	0	0	2	3	22	3.81
6	I found too much inconsistency in the system.	19	6	2	0	0	3.62
7	I think that most students would learn to use this system very quickly.	0	0	4	5	18	3.66
8	I think that the system is very difficult to use.	20	4	3	0	0	3.62
9	I felt very confident using this system.	0	0	2	4	21	3.77
10	I needed to learn a lot of things before I could start learning with this system.	22	2	3	0	0	3.70

In addition, five simple questions asked about different aspects including easiness in interface,

students' mental modeling and their motivation, and satisfaction of field experts, as shown in Table 2.

**Table 2.** Questionnaires from experts about the proposed DVCL.

Q.No	Questions
1	How do you rate that the contents setting mechanism for adding new chemistry experiments in the proposed DVCL is not complex?
2	How do you rate that the proposed DVCL provides sufficient information to consolidate students' mental modeling for hands-on experiments?
3	How do you rate that the proposed DVCL increases students' motivation for hands-on experiments?
4	How do you rate the recommendation of the proposed DVCL in its current form that new students would use prior to their first laboratory experiment?
5	How much are you satisfied with the proposed DVCL?

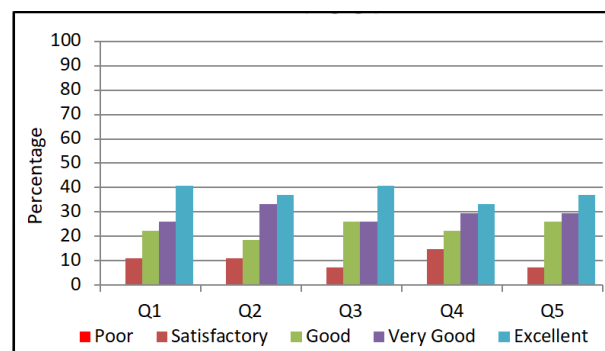
The participants were asked to rate these factors as poor, satisfactory, good, very good, or excellent based on their experience using the proposed DVCL. The following questions asked from each participant. The results are shown in Table 3 and Figure 6. For the first question, which is related to the mechanism for adding new experiment, 22.2% of the experts selected the "Good" option, 25.9% of the experts selected the "Very Good" option and 40.7% of the experts selected the "Excellent" option. It can be concluded that the contents setting mechanism for adding new experiment is not complex. For the second question, which is related to the sufficient information for students' mental modeling, 18.5% of the experts selected the "Good" option, 33.3% of the experts selected the "Very Good" option and 37.0% of the experts selected the "Excellent" option. It can be concluded that DVCL provides sufficient information to consolidate students' mental modeling for hand-on experiments. The third question which is related to the students' motivation, 25.9% of the experts selected the "Good" option, 25.9% of the experts selected the "Very Good" option and 40.7% of the experts selected the "Excellent" option. It means that the proposed DVCL is suitable to increase students' motivation for hand-on experiments. The fourth question which is related to the recommendation of the DVCL for new students, 22.2% of the experts selected the "Good" option, 29.6% of the experts selected the "Very Good" option and 33.3% of the experts selected the "Excellent" option. It can be concluded that for new students the proposed DVCL is suitable to use prior for their first laboratory experiment. The last question, regarding the experts' satisfaction from the proposed DVCL, got the vote 25.9%, 29.6% and 37.0% of the experts for the "Good", "Very Good" and "Excellent" options, respectively.

**Table 3.** Experts' Responses about DVCL (Participants= 27).

Q.No	Experts' Responses				
	Poor	Satisfactory	Good	Very Good	Excellent
Q1	0.0%	11.1%	22.2%	25.9%	40.7%
Q2	0.0%	11.1%	18.5%	33.3%	37.0%
Q3	0.0%	7.4%	25.9%	25.9%	40.7%
Q4	0.0%	14.8%	22.2%	29.6%	33.3%
Q5	0.0%	7.4%	25.9%	29.6%	37.0%

To summarize the above subjective analysis, experts were overall satisfied with various aspects of the DVCL. The main aspects include the understandability of the system, the mechanism of the contents setting, and students' motivation for hands-on experiments. Similarly, the system was evaluated with SUS questionnaire [4] and yielded a value of 93.51 which indicates a significant achievement in the usability. Overall, the evaluation results show that the DVCL is

important in teaching chemistry because it trains and motivates students to conduct hands-on experiments, particularly new experiments.

**Fig. 6.** Feedback from Experts.

## 4. Conclusions

In this paper, we proposed a dynamic virtual chemistry lab (DVCL) where instructors or experts are allowed to add a new chemical experiment by adding its apparatus, chemicals, glassware, and mechanism or add something new to its properties. We conducted a subjective study with field experts to investigate the effect of proposed DVCL in secondary school chemistry education. During evaluation, twenty-seven field experts were participated and evaluated the proposed DVCL with system usability scale (SUS)-questionnaire [4] and by a simple questionnaire. The results showed that the proposed DVCL is very helpful for students' performance and mental modeling and also for effortlessly uplifting their knowledge for hands-on experiments.

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## Author Contributions

NA has development of the research project and writing of literature review and methodology. SU, and AF performed the supervision, validation and correcting the contents of the writing. SRF, SS, and JR control the writing of articles so that they comply with the guidelines for writing good and correct papers.

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