Hybridizing Real and Virtual Experiences: Inquiry-Based Learning Activities to Explore Surface Chemistry

Kong-Ching Wong [a]*, K. Brant Knutzen[b], Ignatius IP[a], Steve Po-Yam LI[a]

[a]*Department of Pharmacology and Pharmacy, The University of Hong Kong, Hong Kong Special Administrative Region, 999077, People of Republic China*

[b]*[Global Educational Consulting, see Brant.Knutzen.se]*

*Email: kcwong47@hku.hk

ABSTRACT

Surface chemistry is a challenging realm for most students owing to its abstract nature and the numerous associated mathematical equations. Herein, we report a set of dedicated sequential inquiry-based learning (IBL) activities enriched with virtual laboratory learning and hands-on instructions. The activities were intended to help students grasp the abstract concepts and understand the mathematical equations related to surface chemistry. The activities included two methods for measuring surface tension: the capillary rise method and drop weight method. In addition, students were guided to observe the adsorption phenomenon and critical micelle concentration (CMC). The activities were implemented in a second-year pharmaceutical chemistry course for pharmacy undergraduate students. Feedback from the students indicated that the activities could nurture their interest in the topics. Moreover, we have proven that hybridizing virtual learning and hands-on learning in IBL is viable and could offer positive effects on students' learning. We advocate the use of virtual laboratories to support IBL activities in the post-pandemic era.

KEYWORDS

Second-year Undergraduate, Physical Chemistry, Computer-based Learning, Inquiry-based/Discovery Learning, Surface Sciences

INTRODUCTION

Although chemistry is an indispensable component of pharmacy education, pharmacy students often find this subject challenging,probably because the chemical sciences deal with the phenomena that occur at the atomic-molecular level. Excelling in it requires the students to make dexterous transitions between three levels of representation: macroscopic, submicroscopic, and symbolic.[1-8] Inquiry-based learning (IBL) could be a solution for instructors and students to address this challenge. In IBL, students construct and intentionally discover knowledge by themselves through a repeated learning cycle comprising three phases: exploration, concept invention, and application.[4-8]

In a laboratory-based IBL activity, the most obvious limiting factor is the conformity of the experimental data to the theory being taught. These data are used by the students to build their own conceptual models in the concept invention phase. If the data deviate too much from the theory, students' conceptual understanding may be tempered or even diverted to alternative concepts (i.e., misconception).[9, 10]

An 3D immersive virtual learning environment (a virtual laboratory) offers a solution to this problem. In a virtual laboratory, everything is regulated by the rules and algorithms set by the programmer. The conditions and experimental data can conform to the theories as long as the designer of the virtual environment deems it appropriate. In such an environment, students could construct their conceptual models with minimal interference and cognitive loads arising from unexpected events in the real world.

Herein, a set of sequential IBL activities conducted in both a virtual laboratory and a physical laboratory is reported. These activities were implemented in a second-year pharmaceutical chemistry course (BPHM2133) under the Bachelor of Pharmacy program at the University of Hong Kong. This course covered basic physical chemistry topics such as thermodynamics, acids and bases, solubility, interfacial chemistry, rheology, and polymers. The learning activities reported herein focused on the method of teaching interfacial chemistry. The intended learning objectives were:

After completing these learning activities, students will be able to:

1. Measure surface tension using the capillary rise method
2. Measure surface tension using the drop weight method
3. Discover and apply the adsorption phenomena

4. Discover and apply the critical micelle concentration (CMC)

Readers may refer to the Supporting Information (SI01) for the theories underlying the capillary rise and drop weight methods.

We noticed that in a recent work published by Gencer et. al,[11] a set of comprehensive guided-inquiry activities for training preservice teachers was reported. Our study, in contrast, is intended to foster undergraduate learning. To the best of our knowledge, this is the first IBL activity on surface tension–related topics for undergraduate students.

PEDAGOGICAL STRATEGY

For years, our students have reported that surface tension is an abstract and challenging subject. Therefore, we decided to employ IBL in the context of a virtual laboratory to help students learn the subject. The overall strategy was to first use a virtual laboratory to guide the students to discover the usefulness of capillary tubes and pipettes for measuring surface tension. Then, the students practiced and familiarized themselves with the capillary rise method and the drop weight method in a face-to-face physical laboratory session. Next, the students used the pipettes (i.e., the drop weight method) to measure the surface tension of various ethanolic aqueous solutions, and were guided to study the effects of solute concentration on surface tension. Finally, the students measured the surface tension of a set of surfactant solutions and were guided to discover and apply the CMC.

Figure 1 below shows a summary of the pedagogical strategy.

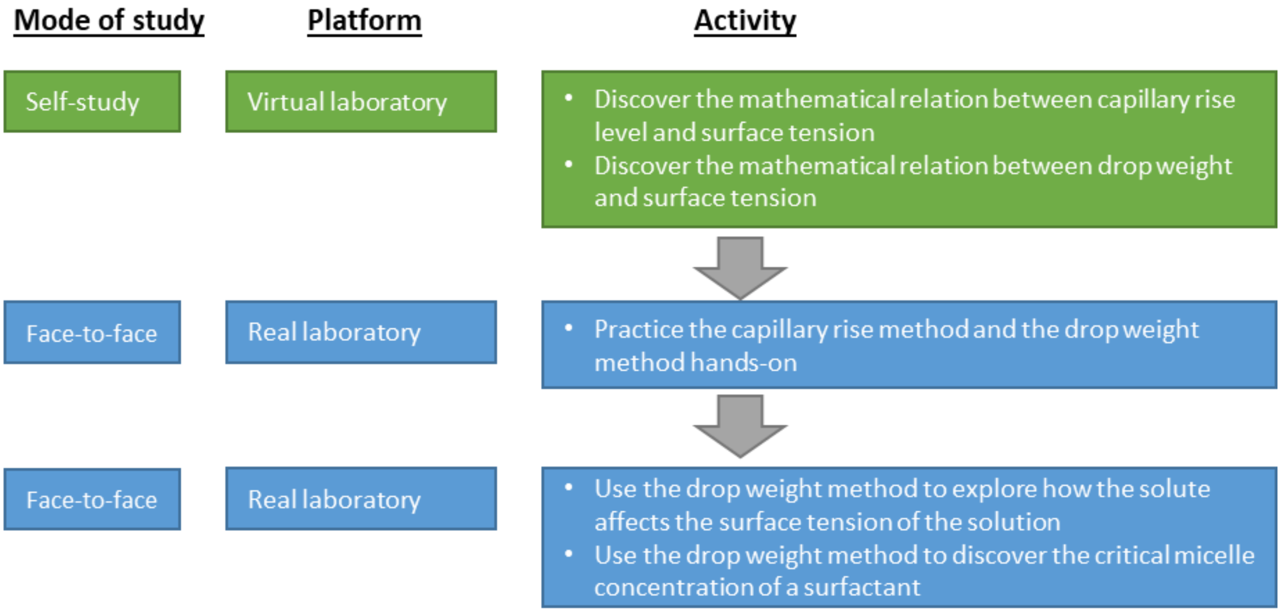


Figure 1. The pedagogical strategy and flow of the teaching activities.

MATERIALS AND METHODS

Participants

The activities were designed for the second-year pharmacy undergraduates taking the course BPHM2133 Pharmaceutical Chemistry. All students enrolled in the course were required to attend the virtual laboratory experiments and the face-to-face laboratory activities. The survey at the end of these activities, however, was voluntary. This was to ensure that in case a student was reluctant to participate in the survey, he/she would not be at a disadvantage or treated unequally, and he/she would receive the same quantity and quality of instruction as the other students. A total of 35 students participated in the activities. They were divided into groups of three or four. Each student was assigned a specific role (Table 1). The learning activities consisted of virtual laboratory experiments and face-to-face physical laboratory activities.

Table 1. Roles and Responsibilities Throughout the Learning Activities

Role	Responsibility
Manager	Submit assignments before the deadline
Scientist	Design and conduct experiments
Analyst	Data analysis

Informed consent was obtained from all participants of the survey. This study was reviewed and approved by the institutional review board of the university.

Design of the Virtual Laboratory Experiments

The virtual laboratory was built using the 3D immersive virtual environment Second Life.[12] The laboratory was situated on an island, which contained buildings (laboratories) as well as a garden and kiosks. The virtual laboratory was composed of five identical laboratories scattered around the island. Students' avatars could navigate from one laboratory to another to greet their classmates and explore the garden. Given the size of the laboratory, each was equipped with two benches. Owing to the complexity of programming, each bench could only allow concurrent operation by two students, while others could observe the students conducting the experiment, as a group of avatars in the virtual laboratory

The server of the 3D virtual laboratory could handle up to twenty users simultaneously without any noticeable lag. To prevent a surge of students onto the server simultaneously just before the deadline, each group was assigned a dedicated timeslot for using the virtual laboratory.

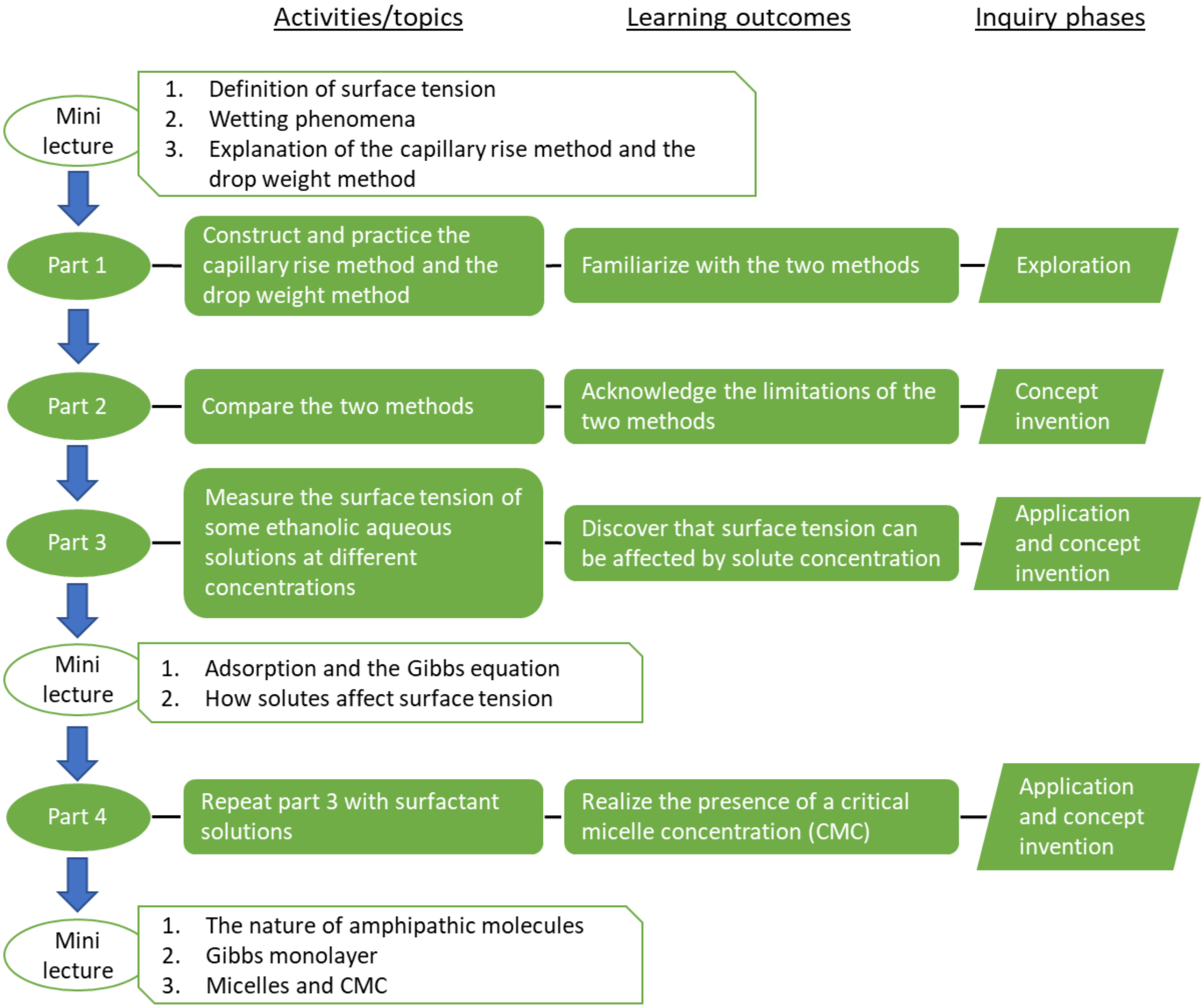
Simulations were run for two sets of inquiry-based experiments. The first set was based on the capillary rise method, and the second set was based on the drop weight method. Each set was divided into three parts, enabling the students to explore various parameters that could affect the results of the experiments based on the two methods, and to apply them to the measurement of the surface tension of different liquids. A laboratory manual for the virtual experiments, which contained step-by-step instruction and questions regarding experimental data, was also provided to the students.

A random error ($\pm 10\%$, rectangular distribution) was incorporated into the virtual experiments.[13] We believed this could enhance realism and discourage the copying of answers among classmates.

This virtual laboratory was not intended to facilitate kinesthetic training, but instead focus on the construction of conceptual understanding. Its operation relied on a two-dimensional screen, a keyboard, and a mouse, so this interface was not designed to emulate the sensorimotor feedback that one would experience in the real world.[14] The hands-on kinesthetic training, on the other hand, was delivered in the face-to-face laboratory activities.

Design of the Face-to-Face Laboratory Activities

The face-to-face laboratory activities were scheduled after the virtual experiments. As shown in Figure 2, the activities consisted of several parts, including mini lectures, hands-on experiments, and group discussions. Part 1 was essentially the repeat of the virtual laboratory experiments, aiming at allowing the students to gain hands-on experience and familiarize themselves with the two methods. Part 2 was a group discussion for the students to compare the two methods. In part 3 and part 4, the students used the drop weight method to measure the surface tension of a series of aqueous ethanolic solutions and surfactant solutions. In theory, the capillary rise method should also work for these two parts, but the authors found the drop weight method was easier to use.



115 Figure 2. Flow of the face-to-face laboratory activities. Hollow textboxes are the mini lectures. Solid textboxes are the inquiry activities.

The students were provided with a worksheet for recording the data and observations in the face-to-face laboratory activities.

The materials needed to conduct the activities are listed in Table 2.

120

Table 2. Materials Required for the Face-to-Face Laboratory Activities (Each group)

Part 1	
Capillary Rise Method	
Materials	Quantity
Stand	1
peg	2
Ruler	1
Capillary tubes[a]	Handful
Test tubes	5
Test liquids[b]	1 set
Drop Weight Method	
Materials	Quantity
Stand	1
Clamp	2
50 mL conical flask	1
Plastic pipette[c]	Handful
4-digit electronic balance	1
Test liquids[b]	1 set
Part 3	
Materials	Quantity
Drop weight method set (excluding the test liquids)	1
Ethanol aqueous solutions[d]	1 set
Part 4	
Materials	Quantity
Drop weight method set (excluding the test liquids)	1
Surfactant aqueous solutions[e]	1 set

[a] Inner diameter is either 0.3 mm or 0.5 mm;

[b] Water, acetone, ethanol, 2-propanol, methanol, chloroform, dimethylformamide, hexane, acetonitrile, ethyl acetate, tetrahydrofuran;

[c] Low density polyethylene (LDPE), inner diameter is 2.2 mm;

[d] Water:ethanol (v/v) = 10:0, 9:1, 8:2, …, 1:9, 0:10);

[e] A domestic dishwashing liquid was used. For the preparation, please refer to the Supporting Information (SI07).

For capillary rise measurements, a modified version of the method reported by Munguia[15] was used. In the modification herein (Figure 3A), a peg was used to hold the capillary tube vertically and static. This allowed the capillary to remain in contact with the liquid while the students measured the rise in its level. Rulers were used instead of vernier calipers for simplicity in measurements. The measurements were recorded using the naked eye.

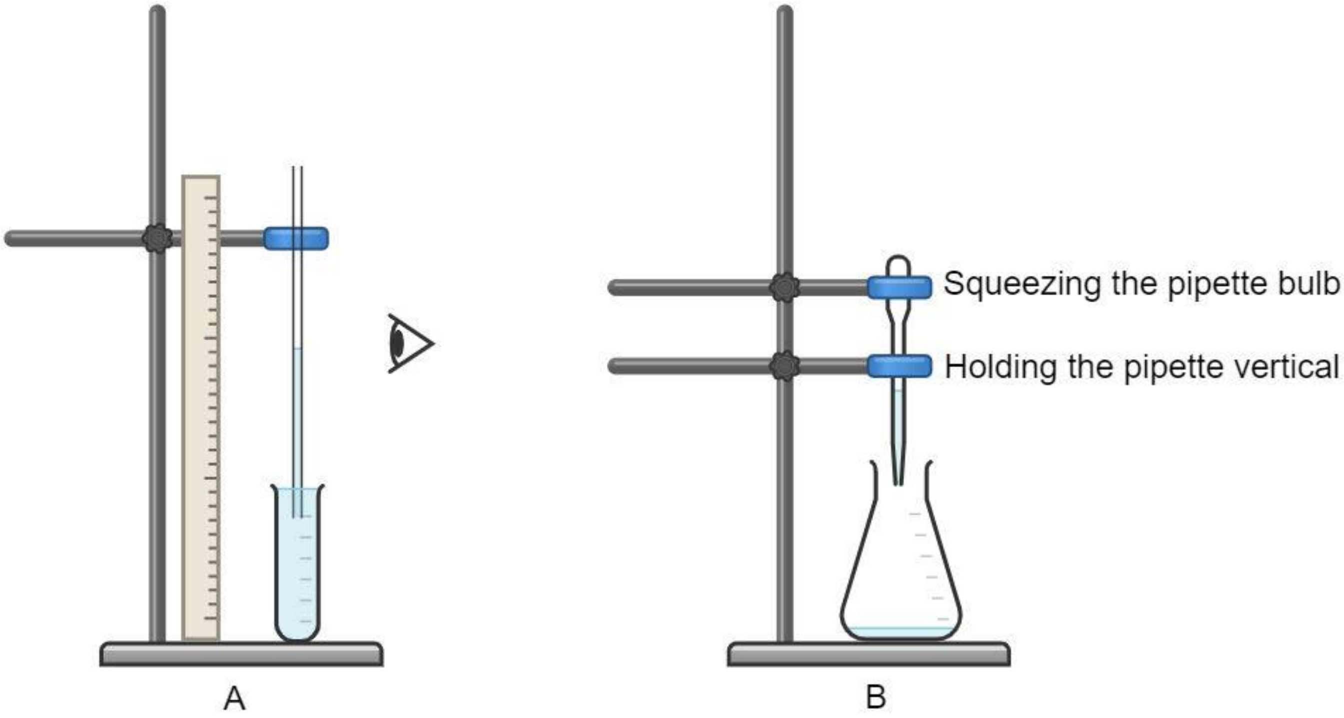


Figure 3. Experiment setup for (A) capillary rise method and (B) drop weight method.

The drop weight measurement method was adopted based on the method reported by Gascon.[16] Herein, the pipette was fastened using a clamp to ensure it was vertical when dispensing the liquid (Figure 3B). A second clamp was fastened to the pipette bulb. Turning the second clamp would squeeze the bulb slowly, allowing the dispensing of the liquid to be consistent.

IMPLEMENTATION OF THE ACTIVITIES

As the students in our implementation were not majoring in science, the virtual laboratory activities were delivered with detailed instructions and guidance. Readers could customize the activities to increase the level of inquiry based on the background of their students. For example, instructors can remove the stepwise procedures in the manual of the virtual experiments and ask the students to design an experiment to figure out how to use capillary tubes/pipettes to measure surface tension. Readers may refer to the Support Information (SI07) for more details.

During the first lecture of the course, the instructor briefed the students about the details of the study, including the idea of IBL and the learning cycle (i.e., exploration, conception construction, and application), the purposes of the study, the 3D virtual laboratory, and the presence of random error in the virtual experiments.

Virtual Experiments

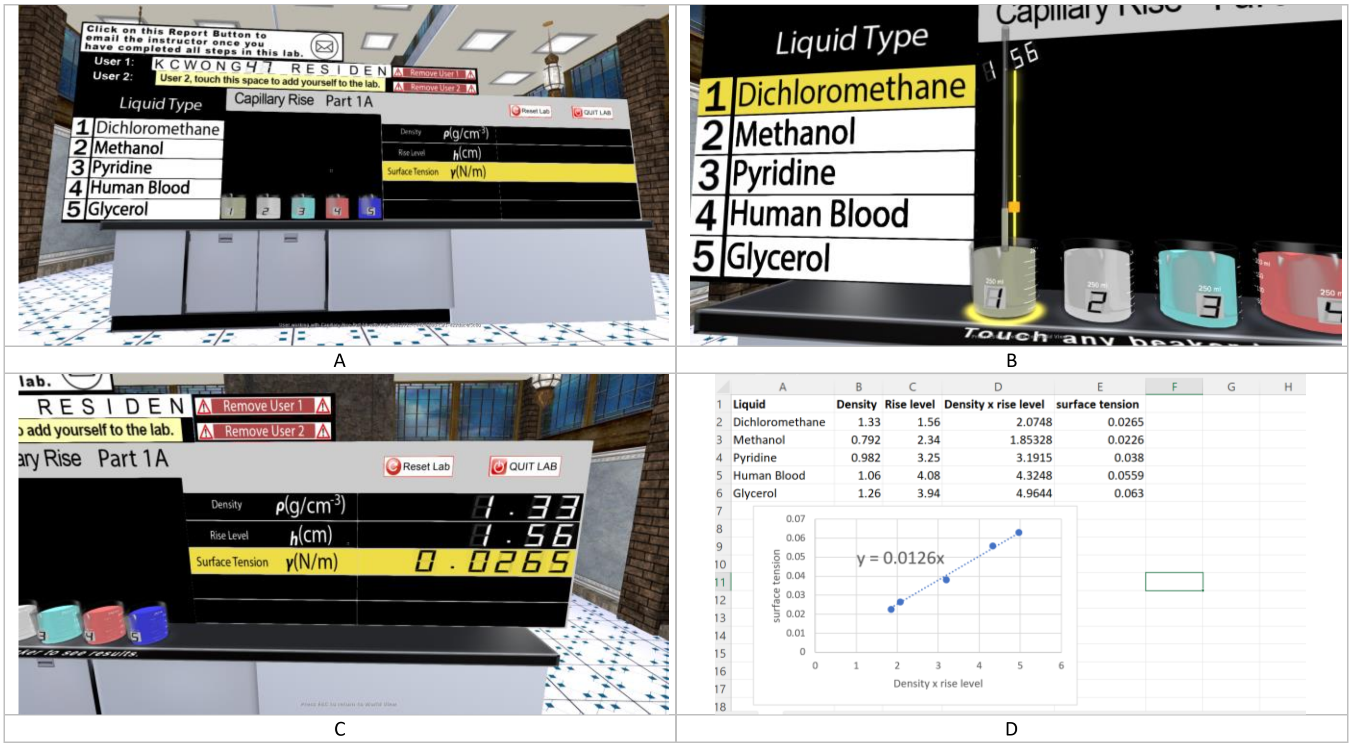
The virtual experiments were conducted before the face-to-face laboratory sessions. The students logged into the virtual laboratory to complete the experiments in groups according to the laboratory manual. The manager of each group was required to submit the resulting data into Moodle as a form of assessment. There were in total six experiments in the virtual laboratory (Table 3).

Table 3. Details of the Six Experiments in the Virtual Laboratory

Experiment	Task	Inquiry elements
Set 1, Part 1A	1. Measure the capillary rise levels of five liquids with known surface tension and density 2. Plot rise levels against surface tension and density	**Exploration**: the capillary effect and how surface tension (γ) and density (ρ) affect rise level (h). **Invention**: the empirical equation that relates γ, ρ, and h (i.e., $h \propto \frac{\gamma}{\rho}$).
Set 1, Part 1B	Measure the surface tension of water, ethanol, and 2-propanol.	**Application**: use the empirical equation discovered in part 1A to measure the surface tension.
Set 1, Part 2	1. Measure the rise levels with capillary tubes of different inner radii. 2. Plot rise levels against inner radii	**Exploration**: how inner radius (r) affects rise level (h) **Invention**: the empirical equation that relates r and h (i.e., $h \propto \frac{1}{r}$).
Set 2, Part 1	1. Measure the drop weights of five liquids with known surface tension. 2. Plot drop weights against surface tension	**Exploration**: how surface tension (γ) affects drop weight (m). **Invention**: the empirical equation that relates γ and m (i.e., $m \propto \gamma$).
Set 2, Part 2	Measure the surface tension of an unknown liquid.	**Application**: use the empirical equation discovered in part 1 to measure the surface tension.
Set 2, Part 3	1. Measure the drop weights with pipettes of different inner radii. 2. Plot drop weights against inner radii	**Exploration**: how inner radius (r) affects drop weight (m). **Invention**: the empirical equation that relates r and m (i.e., $m \propto r$).

For instance, in the capillary rise experiment (Table 3, set 1, part 1A), the students could see five beakers of liquids on the bench (Figure 4A). When they clicked any beaker, they would see a capillary tube being lowered into the liquid, and the liquid would be drawn up by the capillary tube (Figure 4B).

The blackboard on the right-hand side would show the density of the selected liquid, the rise level, and its surface tension (Figure 4C). The students repeated the measurement on the other four liquids and recorded the data on an Excel spreadsheet (Figure 4D). Next, they were instructed to generate a plot of surface tension against the products of densities and rise levels (Figure 4D). Up to this point, the students had explored the capillary effect and noticed that there was some relationship between rise level and surface tension. Next, the students were asked to propose an empirical equation to describe that relationship. This was where the students started to construct concepts and build their conceptual models. Note that in Figure 4D, some points deviate from the regression line. This is due to the random error incorporated into the virtual laboratory. Finally, the students needed to submit their equations onto Moodle for marking.



Liquid	Density	Rise level	Density x rise level	surface tension
Dichloromethane	1.33	1.56	2.0748	0.0265
Methanol	0.792	2.34	1.85328	0.0226
Pyridine	0.982	3.25	3.1915	0.038
Human Blood	1.06	4.08	4.3248	0.0559
Glycerol	1.26	3.94	4.9644	0.063

A B

C D

Figure 4. (A) Experiment set 1 part 1A. There were five beakers of liquids on the bench. The left board displayed which liquid is selected. The right board displayed the density, rise level, and surface tension of the selected liquid. (B) A capillary tube was lowered into the liquid. The left board indicated the liquid is dichloromethane. The liquid was drawn up by the capillary tube. The rise level was shown as 1.56. (C) The right board simultaneously displayed the physical parameters. (D) An Excel spreadsheet recorded the data. The plot underneath indicated the empirical equation was $\gamma = 0.0126(\rho)(h)$, where γ: surface tension, ρ: density, and h: rise level.

The second example is the drop weight experiment (Table 3, Set 2 part 1). The students could see, from the left to the right, an electronic balance, a stand with clamps, a conical flask, five beakers of liquids (1. Hexane, 2. Ethanol, 3. Quinoline, 4. Glycerol, 5. Water), and a pipette (Figure 5A). The students clicked the conical flask to place it under the stand. Then, the students selected one of the five beakers. The pipette moved to that beaker and started drawing up liquid. Next, the pipette moved to the stand and was clamped as shown in Figure 5B. The pipette then delivered 20 drops of the liquid to the conical flask. The flask was then weighed, and the mass was displayed on the screen of the balance (Figure 5C). The students then repeated the measurement on the other four liquids and recorded the data on an Excel spreadsheet (Figure 5D). After that, they were instructed to generate a plot of surface tension against drop weight. From that, they would find there was a certain relationship between surface tension and drop weight. They were then asked to describe that relationship using an equation.

Liquid	Drop weight (20 drops)	Surface tension
Hexane	0.4995	0.0184
Ethanol	0.6332	0.0252
Quinoline	1.1194	0.0431
Glycerol	1.6697	0.0640
Water	1.7983	0.0728

Figure 5. (A) Experiment set 2 part 1. There was a balance, a conical flask, a pipette, and five beakers of liquids. (B) The pipette charged with liquid was held by the clamps. The liquid was being dispensed dropwise into the conical flask underneath. Twenty drops were dispensed. (C) The dispensed liquid was weighed by an electronic balance. The mass was 0.4995 g. (D) An Excel spreadsheet records the data. The plot underneath indicates the empirical equation is $\gamma = 0.0393m$, where γ: surface tension, m: drop weight.

For the detailed illustration of the other four virtual experiments, readers may refer to Table 3 and the Supporting Information (SI06).

Face-to-Face Laboratory Activities

It is worth noting that upon completing the virtual experiments, the students only learned the following factual phenomena and some empirical equations.

- Capillary rise level is affected by the surface tension of the liquid and the inner radius of the capillary tube
- Drop weight is affected by the surface tension of the liquid and the inner radius of the pipette
- Capillary tubes and pipettes can be used to measure surface tension

Thus, it was necessary for the instructor to introduce, in the mini-lecture, the basic concepts of surface tension and the explanations of the two methods, including deriving the complete forms of the two equations (Scheme 1).

$$\text{Capillary rise: } \gamma = \frac{r\rho g h}{2} \qquad \text{Drop weight: } \gamma = \frac{mg}{2\pi r}$$

Scheme 1. γ: surface tension, r: inner radius, ρ: density, g: gravity, h: rise level, m: drop weight

Then, the instructor asked the students to use the materials available on their benches to reconstruct the capillary rise and drop weight experiments that they had conducted in the virtual laboratory. The instructor provided minimum guidance allowing the students to figure out the experimental setups and solve technical challenges by themselves with the highest degree of autonomy. This also encouraged the students' problem-solving skills, ability to collaborate, and critical thinking. The instructor would intervene only when there was a sign of complete failure in the experimental setup or a potential hazard. In our implementation, all the student groups managed to reconstruct both experiments. Students generally found the realization of the capillary rise method more challenging as they decided to hold the capillary tube upright by hand to measure the rise level rather than using a peg. Similarly, some groups squeezed the pipette bulb by hand instead of using a clamp. This could decrease the accuracy of the experimental output,however, it couldnot pose any negative impact on the students' learning. Figure 6 shows the setups of the two experiments optimized by our technical colleagues.

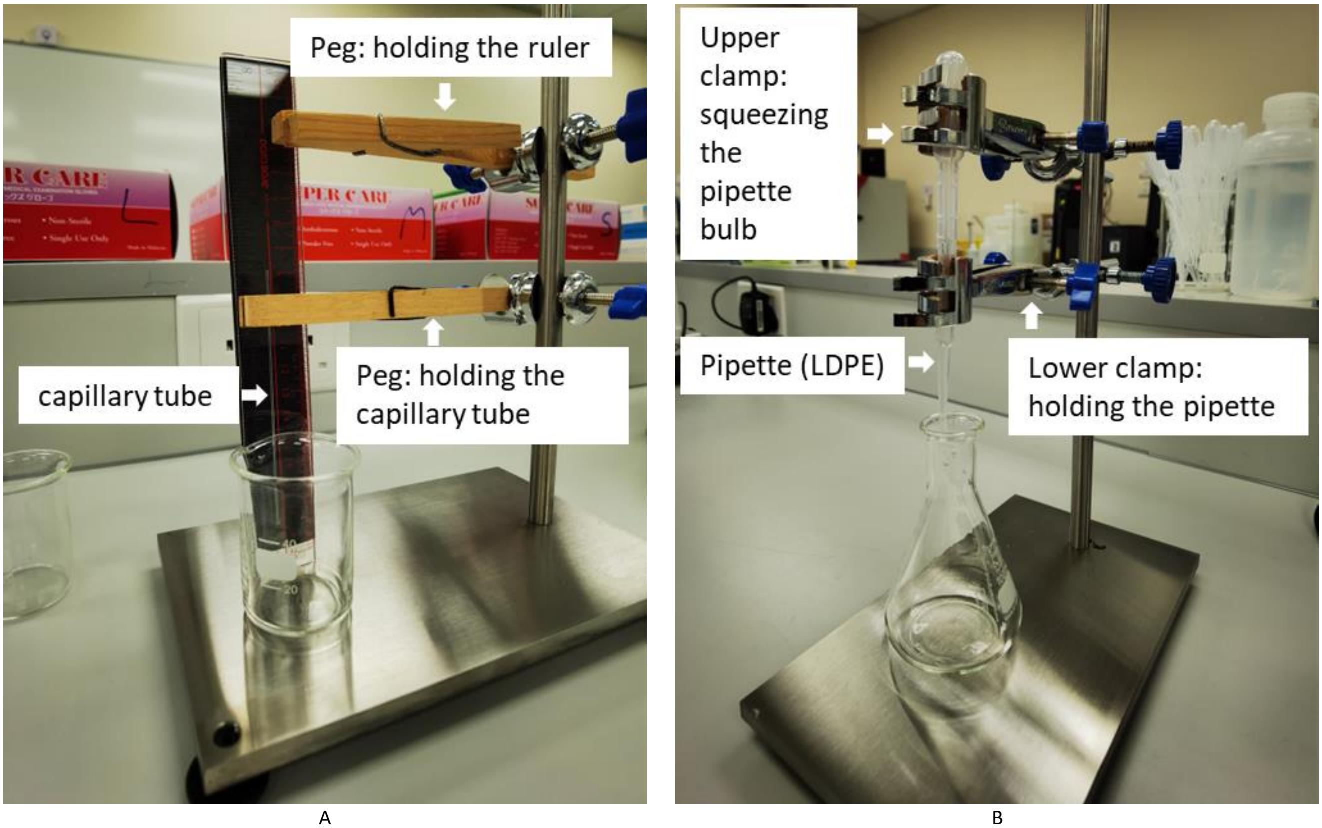


Figure 6. Optimized experimental setups constructed by technical colleagues. (A) Capillary rise. (B) Drop Weight; LDPE: low density polyethylene

Then, the students selected five liquids from the eleven test liquids provided and used their setups to measure the surface tension of the liquids. The instructor provided the students with the density of the liquids, the inner radii of the capillary tubes and the pipettes for calculating surface tension. The groups were advised to use the same five liquids for conducting both methods to enable a meaningful comparison.

The instructor further instructed the students to discuss and decide which method they would prefer. The students could choose either method as long as they could justify their choice. Herein, most groups chose the drop weight method owing to its reliability. However, a few groups chose the capillary rise method because it is faster than the drop weight method (the drop weight method required the weighing of 20 drops of liquid falling from the pipette to obtain the average error value).

Then, the students were instructed to use the drop weight method to measure the surface tension of numerous ethanolic aqueous solutions of different concentrations. The instructor collected the data from the groups and plotted a graph of the surface tension against concentration. An example of this graph is shown in Figure 7A. When the graph was shown to the students, they immediately remarked that the presence of an organic solute decreased the surface tension of the solution. Furthermore, this decrease in the surface tension of the solutions was proportional to their concentrations.

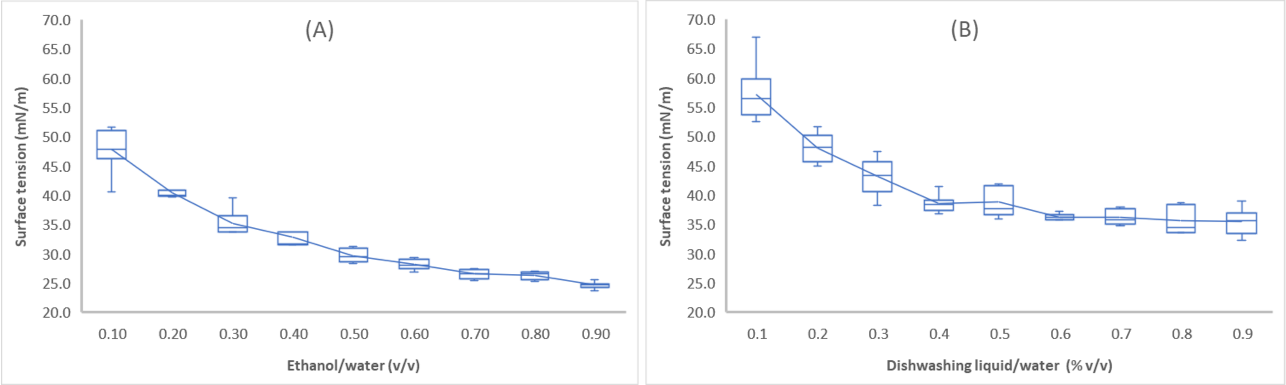


Figure 7. Plots of surface tension against concentration levels. Data were collected from student groups. (A) Ethanol was used as the solute. The surface tension dropped continuously as more ethanol was added. (B) A domestic dish washing liquid was used as the solute. The surface tension decreased at the beginning but reached a plateau at approximately 0.4% v/v, indicating that the CMC was reached. Beyond this point, the surface tension became steady.

Subsequently, the instructor introduced the concept of adsorption and explained that the presence of an organic solute in the interfacial region could disrupt the intermolecular interaction and thus reduce the surface tension. In our implementation, the effect of ionic solutes (e.g., NaCl) was not demonstrated. In theory, salt is negatively adsorbed on the interface and it should augment the surface tension. However, such an increase is extremely small and cannot be measured using the comparatively primitive drop weight method. Therefore, the instructor only described the phenomenon to the students.

In the concluding part, the students repeated the experiments using a number of surfactant solutions. Domestic dishwashing liquid was used herein. Because the precise concentration of the surfactant was unknown, a technical colleague was instructed to prepare a wide range of solutions and determine the CMC in advance. For easy visualization, the final concentrations used to conduct the experiments were selected such that the CMC was located at approximately the center of the graph. An example is shown in Figure 7B. The curve reached plateau above the concentration 4% (v/v), indicating the CMC of the domestic surfactant was reached.

Finally, the instructor introduced the concepts of amphipathic molecules, the Gibbs monolayer, and the formation of micellar structures at concentration levels beyond the CMC. Because this course was for pharmacy students, the instructor concluded the activities with a discussion on the use of micelles in drug delivery systems (e.g., liposomes, mRNA vaccines, extracellular vesicles, etc.).

RESULTS AND DISCUSSION

Students' Performance in the Virtual Experiments

Upon examining the students' answers on Moodle, the instructor reported that most student groups had obtained the empirical equations and used these equations to determine the surface tension. The instructor also noted some common mistakes:

- Answers were presented with a wrong order of magnitude
- Answers were presented with a wrong unit
- Confusion between the abscissa and the ordinate

Accuracy and Precision

In our implementation, the drop weight method produced more accurate results than the capillary rise method. This was probably because the levels of liquids in the capillary rise method were measured visually, whereas the drop weights in the drop weight method were measured using an electronic balance that could record weights as low as 0.1 mg.

Contrary to Munguia's results [15], the capillary rise results based on our modification were less accurate with respect to the measurement of the surface tension of water. The results deviated by as much as 82% from the nominal value. We suspect that the large surface tension of water might have prohibited the initial wetting process inside of a capillary tube (Supporting Information SI01).

In contrast, the drop weight results in our implementation showed a deviation of only 3%. Based on the study by Gascon[16], nonwetting was necessary to ensure that the radius of the pendant drop could match the orifice radius of the pipette. This requirement could be fulfilled with the aid of the large surface tension of water and the hydrophobic nature of the plastic pipettes (Figure 9A). Moreover, consistent with Gascon's finding, our drop weight method did not work on glass pipettes because the liquid would wet the outer edge of the orifice, leading to variable drop size (Figure 9B).

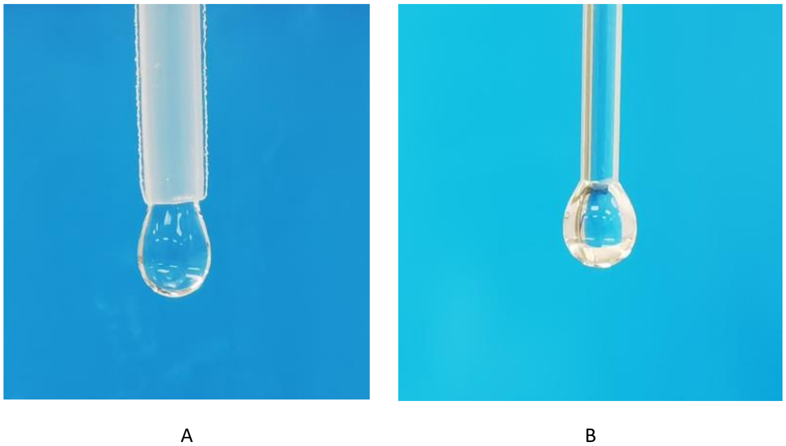


Figure 9. Pendant drops at the orifices of (A) a plastic pipette and (B) a glass pipette before detachment. Due to nonwetting, the size of the pendant drop in (A) is close to the inner radius of the pipette. Upon contact, the pendant drop in (B) wets the outer edge of the orifice. Its size surpasses the inner radius of the pipette.

In terms of precision, the two methods in our implementation demonstrated comparable coefficients of variance. The data pertaining to accuracy and precision are available in the Supporting Information (SI01).

Questionnaire

Twenty-two students (12 males and 10 females) completed and submitted their questionnaires. Most students reported that they had no prior exposure to IBL and virtual learning. We were delighted to find out that the virtual laboratory was positively received by the students (Table 4). In general, the students agreed that the virtual laboratory had a positive influence on their learning and understanding of the topic. No student reported any nausea or unpleasant disorientation associated with the virtual laboratory.

Table 4. Students' Feedback on the Virtual Laboratory

Question	Average score[a]
	$(n = 22)$
1. The virtual laboratory interface is easy to use.	3.6/5
2. The instructions in the virtual laboratory are clear.	3.8/5
3. The virtual laboratory allows me to have more control over my own learning.	3.5/5
4. The experiments in the virtual laboratory could help me understand the course context.	3.5/5
5. The virtual laboratory could familiarize me with the experimental setup in the real world.	3.6/5

[a] Likert scale: strongly disagreed [1] disagreed [2] neutral [3] agreed [4] strongly agreed [5]

Five questions were used to measure and rank the confidence of students on specific topics (Table 5). In general, the students expressed a confident attitude (average score ranges between 3.8-4.0 out of 5.0), suggesting that the learning activities could help the students build confidence in the topic.

Table 5. Confidence in the Topic

Question	Average score[a]
	$(n = 22)$
1. I can explain why liquid rises in a capillary tube.	3.9/5
2. I am confident about performing the capillary rise experiment to measure surface tension.	3.9/5
3. I am confident about performing the drop weight experiment to measure surface tension.	4.0/5
4. I am confident about performing calculations with respect to capillary rise $\left(\gamma = \frac{r\rho g h}{2}\right)$.	3.8/5
5. I am confident about performing calculations with respect to drop weight $\left(\gamma = \frac{mg}{2\pi r}\right)$.	3.8/5

[a] Likert scale: strongly disagreed [1] disagreed [2] neutral [3] agreed [4] strongly agreed [5]

Additionally, two questions were used to directly test the students' understanding (Table 6). The results demonstrate that more than half of the students (68% and 59% respectively) could answer correctly. The authors suggest that after all learning activities were completed, instructors could arrange for a tutorial session (e.g. problem-set tutorial) so that the students could practice what they have learned, and deepen their understanding of the concepts they have invented.

Table 6. Students' Understanding on the Topics

Question	Students' answers
	Yes/No/I am not sure
1. The surface tension of water decreases when an organic solute (e.g. ethanol, detergent) is added.	15[a]/3/4
2. Amphipathic solutes exhibit critical concentrations above which surface tension stops decreasing.	13[a]/1/8

[a] Correct answer

Finally, the students' overall reception of the learning activities was evaluated (Table 7). Multiple instances of positive feedback were observed. In general, the students agreed that the activities were interesting, enjoyable, and could trigger their interest in learning the subject. Moreover, the students' feedback supported the necessity of implementing IBL and virtual learning in the future.

Table 7. Overall Learning Experience

Question	Average score[a]
	$(n = 22)$
1. Overall, the learning activities were interesting.	4.0/5
2. The learning activities provoked my interest in learning the topic.	3.7/5
3. The learning activities stimulated me to learn more.	3.7/5
4. I have gained a good understanding of the basic concepts in this series of learning activities.	3.8/5
5. I was overwhelmed by the vast information in the learning activities.	3.5/5
6. Overall, I found the learning experience enjoyable.	4.0/5
7. There should be more inquiry-based learning in the pharmacy program.	3.6/5
8. There should be more learning activities being conducted in a virtual environment.	3.5/5

[a] Likert scale: strongly disagreed [1] disagreed [2] neutral [3] agreed [4] strongly agreed [5]

However, the students also found the information they had received in the learning activities to be overwhelming (Question 5, Table 7). This was possibly owing to the complex and abstract nature of the topics covered, including surface tension, adsorption, and the differential symbol in Gibb's adsorption equation.

Comments from the Students

Feedback comments from the students were also collected via the questionnaire. All comments received were about the virtual laboratory and none were concerned with the face-to-face laboratory activities. Presumably, the virtual laboratory was a novel concept for the students and had drawn considerable attention from them. The comments were related to three areas as follows:

- User experience
- Learning experience
- Realism of the virtual laboratory

The key comments are presented in Table 8.

Table 8. Students' Comments on the Virtual Laboratory

Area	Positive	Negative
User experience	• Operation in the virtual lab was easy • Experiment steps were easy to follow • Results were instantaneous • Flexible time management	• Maneuvering in the virtual lab was difficult • Technical glitches

Learning experience	• No worries about making mistakes and generating non-conforming data • Helped understand the concepts and familiarize with the experiments	• Face-to-face learning activities would be more memorable
Realism	• The simulated apparatus looks real • Incorporation of random errors in the virtual lab	• Lacking interaction with real apparatus • Lacking motor training

The students shared a mixed set of impressions when asked about navigating the virtual laboratory. While some students found the control of their avatars and camera angles easy and satisfying, others seemed to have problems with these. According to authors' experience in the Second Life virtual worlds, the maneuvering was reasonably easy, and its user interface and controls were similar to those games with first-person view on the market (i.e., using the WASD keys to move the character and the mouse buttons to interact with objects). Moreover, the users could zoom in and out as well as quickly switch between the first-person and shoulder-camera modes simply by rolling the scroll wheel of the mouse. The control problems experienced by some students might have been attributed to the performance of their personal computers (PCs), as Second Life, being a three-dimensional immersive virtual world environment, imposed a substantial workload on the PC hardware. Finally, the instructor of the course did not offer any formal tutorial sessions prior to the activities regarding the basic maneuvering techniques, but merely invited the students to explore the virtual world by themselves. Hence, some students might have found navigating in the virtual laboratory confusing.

Many students also reported that they had encountered some technical problems when they were first accessing the virtual experiments. For example, when a student quit the Second Life Viewer application without logging out of the bench they had been using, it would be suspended and become unusable for other students. Even when the previous user returned, he/she would be deemed a different user, and would be unable to interact with the system and close the bench. Consequently, that bench would become inaccessible until the developer restarted the server. This glitch occurred multiple times when the virtual laboratory was launched initially, causing several benches to become unusable. This problem was resolved by programming the benches to automatically log out users if they were idle for more than 30 minutes.

In terms of the learning experience, one student observed that he/she did not need to worry about making mistakes and obtaining inaccurate data in the virtual laboratory, which highlighted the potential of virtual experiments in facilitating IBL. In a virtual experiment, the conditions are well regulated, and the results are logically governed by algorithms. Thus, it could prevent the generation of any nonconforming data that would otherwise lead to alternative concepts in the concept construction phase of IBL.[9, 10]

Regarding realism, some students expressed that the learning in the virtual laboratory was not as memorable as that in a real laboratory, probably because this virtual laboratory was not intended to facilitate kinesthetic training. Indeed, this is why the activities also included face-to-face sessions in the physical laboratory which were implemented using hands-on activities.

RECOMMENDATIONS

Some student groups had not completed the virtual experiments when they were attending the real laboratory sessions, which could result in a suboptimal learning experience for those students. Thus, we recommended that the students should not be left alone to complete the virtual experiments by themselves. Ideally, instructors should reserve a dedicated session to guide all the students to complete the virtual experiments prior to the face-to-face laboratory sessions.

Instructors should also offer a demonstration session on the keyboard and mouse commands of the virtual platform to facilitate learning by users new to the virtual environment. [13]

CONCLUSION

This study reported a sequential inquiry-based-instructional strategy for teaching surface chemistry. This strategy utilized the merits of both virtual laboratory and real laboratory. The virtual laboratory guided students to discover the empirical equations pertaining to the capillary rise and drop weight methods for measuring surface tension. It also mentally prepared students for the activities in the subsequent face-to-face laboratory sessions. Random errors were incorporated into the virtual experiments to enhance authentic learning. In the physical laboratory activities, the students practiced the capillary rise and the drop weight methods, explored the effects of solutes on surface tension, and developed additional conceptual models regarding adsorption and CMC. These activities were scaffolded by mini lectures explaining the various theories.

The learning activities were conducted for 35 pharmacy second-year students in the year 2022. Evaluation of the activities ($n = 22$) based on four areas (the 3D virtual laboratory, students' confidence in the topic, students' understanding, and overall learning experience) yielded positive and promising results.

The students appreciated the interface of the virtual laboratory. Although no 3D related nausea was reported by the students, some of them encountered difficulties in navigation. This could be related to the performance of their own PCs or inadequate training for new users.

This virtual laboratory was not designed to provide kinesthetic training owing to its hardware limitations (i.e., 2D display, keyboard, and mouse). Instead, this kinesthetic training was delivered through focused face-to-face activities in the physical laboratory.

The results of this study support the hybridized use of virtual laboratories and IBL in teaching abstract concepts, and also shed light on the future of virtual laboratories. In the post pandemic era, the need for virtual laboratories to facilitate distance learning may decline; however, virtual laboratories that support IBL shall continue to thrive. Instructors and programmers may consider developing new virtual learning platforms to support IBL in the future.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.3c00180.

Theories of capillary rise and drop weight, accuracy and precision data (PDF, DOCX)

Lab manual for the virtual experiments (PDF, DOCX)

Worksheet for the face-to-face laboratory sessions (PDF, DOCX)

Experimental data (PDF, DOCX)

Questionnaire (PDF, DOCX)

Illustration of the virtual experiments (drop weight method) (PDF, DOCX)

Notes to instructors (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

Kong-Ching Wong – *Department of Pharmacology and Pharmacy, The University of Hong Kong, Hong Kong Special Administrative Region, 999077, People of Republic China*

*E-mail: kcwong47@hku.hk

Authors

K. Brant Knutzen – *Global Educational Consulting, see Brant.Knutzen.se website for additional information about research projects.*

**E-mail: Brant@Knutzen.se*

Ignatius Ip – *Department of Pharmacology and Pharmacy, The University of Hong Kong, Hong Kong Special Administrative Region, 999077, People of Republic China*

*E-mail: igna1130@hku.hk

Steve Po-Yam Li – *Department of Pharmacology and Pharmacy, The University of Hong Kong, Hong Kong Special Administrative Region, 999077, People of Republic China*

*E-mail: spyli@hku.hk

ACKNOWLEDGMENTS

The authors acknowledge the Teaching Development Grants (project no. 829) at the University of Hong Kong for funding. The authors would also like to thank Mr S. H. Man and all other department technical colleagues for their supports in running the activities. Finally, the authors would like to thank the participating students for their insightful comments.

REFERENCES

(1) Talanquer, V. Macro, Submicro, and Symbolic: The many faces of the chemistry “triplet”. *International Journal of Science Education* **2011**, *33* (2), 179-195. DOI: 10.1080/09500690903386435.
(2) Johnstone, A. H. TEACHING OF CHEMISTRY - LOGICAL OR PSYCHOLOGICAL? *Chemistry Education Research and Practice* **2000**, *1* (1), 9-15, 10.1039/A9RP90001B. DOI: 10.1039/A9RP90001B.
(3) Johnstone, A. H. Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning* **1991**, *7* (2), 75-83. DOI: https://doi.org/10.1111/j.1365-2729.1991.tb00230.x.
(4) Eberlein, T.; Kampmeier, J.; Minderhout, V.; Moog, R. S.; Platt, T.; Varma-Nelson, P.; White, H. B. Pedagogies of engagement in science A COMPARISON OF PBL, POGIL, AND PLTL. *Biochemistry and Molecular Biology Education* **2008**, *36* (4), 262-273. DOI: https://doi.org/10.1002/bmb.20204.
(5) Spencer, J. N. New directions in teaching chemistry: A philosophical and pedagogical basis. *Journal of Chemical Education* **1999**, *76* (4), 566-569. Education Collection; Medical Database; Research Library; SciTech Premium Collection.
(6) Farrell, J. J.; Moog, R. S.; Spencer, J. N. A Guided-Inquiry General Chemistry Course. *Journal of Chemical Education* **1999**, *76* (4), 570. DOI: 10.1021/ed076p570.
(7) Bodner, G. M. Constructivism: A theory of knowledge. *Journal of Chemical Education* **1986**, *63* (10), 873. DOI: 10.1021/ed063p873.
(8) Abraham, M. R.; Renner, J. W. The sequence of learning cycle activities in high school chemistry. *Journal of Research in Science Teaching* **1986**, *23* (2), 121-143. DOI: https://doi.org/10.1002/tea.3660230205.
(9) Pyatt, K.; Sims, R. Virtual and Physical Experimentation in Inquiry-Based Science Labs: Attitudes, Performance and Access. *Journal of Science Education and Technology* **2012**, *21* (1), 133-147. DOI: 10.1007/s10956-011-9291-6.

(10) Jong, T. d.; Linn, M. C.; Zacharia, Z. C. Physical and Virtual Laboratories in Science and Engineering Education. *Science* **2013**, *340* (6130), 305-308. DOI: doi:10.1126/science.1230579.

(11) Gencer, S.; Ekici, F. Preservice Chemistry Teachers' Understanding of Surface Tension through Guided-Inquiry. *Journal of Chemical Education* **2022**, *99* (12), 3946-3953. DOI: 10.1021/acs.jchemed.2c00330.

(12) *Second Life*. 2022. https://secondlife.com/ (accessed 2022.

(13) Winkelmann, K.; Keeney-Kennicutt, W.; Fowler, D.; Macik, M. Development, Implementation, and Assessment of General Chemistry Lab Experiments Performed in the Virtual World of Second Life. *Journal of Chemical Education* **2017**, *94* (7), 849-858. DOI: 10.1021/acs.jchemed.6b00733.

(14) Miles, H. C.; Pop, S. R.; Watt, S. J.; Lawrence, G. P.; John, N. W. A review of virtual environments for training in ball sports. *Computers & Graphics* **2012**, *36* (6), 714-726. DOI: https://doi.org/10.1016/j.cag.2012.04.007.

(15) Munguia, T.; Smith, C. A. Surface Tension Determination through Capillary Rise and Laser Diffraction Patterns. *Journal of Chemical Education* **2001**, *78* (3), 343. DOI: 10.1021/ed078p343.

(16) Gascon, K. N.; Weinstein, S. J.; Antoniades, M. G. Use of Simplified Surface Tension Measurements To Determine Surface Excess: An Undergraduate Experiment. *Journal of Chemical Education* **2019**, *96* (2), 342-347. DOI: 10.1021/acs.jchemed.8b00667.