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Can virtual labs become a new normal? A case study of Millikan's oil drop experiment

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Abstract

The present digital era has brought a paradigm shift in the learning behaviour of students and has provided innovative teaching and learning strategies that extend beyond the four walls of a classroom or a laboratory. One such innovation is the implementation of online or virtual laboratories. A virtual lab is seemingly an economically feasible and effective means to reach out to large audiences in schools, colleges, and universities. In a virtual lab, software simulates the lab environment and provides a step-by-step opportunity to perform an experiment, which can be performed anywhere, any time, on mobile or a notebook or a laptop. Millikan's oil drop (MOD) experiment is one of the key experiments performed in the broad area of modern physics by undergraduate students to estimate the value of charge on an electron and confirm its quantization. Performing this landmark experiment requires good hands-on experimental skill with a lot of patience. It involves managing various parts of the equipment in sync with an effort to keep a charged oil drop in the field of view of the telescope in the presence of gravitational force, buoyant force, viscous force of air and electric force. It simultaneously requires recording of the observations during the upward and downward motion of the charged drops. This paper presents a study to understand the efficacy of performing the MOD method in a virtual environment vis-à-vis the learning outcomes of the students. The study revealed that there was an improvement in the conceptual understanding of the students. The students appreciated the use of the virtual lab, but at the same time they did not see it as a replacement for the traditional method involving an actual laboratory and teachers: they still have an urge to touch and feel the real apparatus in the presence of a human facilitator to clear their doubts.

Keywords: virtual lab, Millikan's oil drop, efficacy

(Some figures may appear in colour only in the online journal)

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1. Introduction

Theory and laboratory practicals are the two major components of traditional science education set-ups. In a traditional laboratory environment, a student tries to achieve a given aim by performing a given experiment through collection of measured data, calculation of relevant physical quantities with errors, drawing inferences, finding the sources of error and presenting the conclusions. Performing the experiments in a laboratory and analyzing the data obtained not only helps in inculcating a scientific temper and logical thinking among students but also develops observational, visualizational and reporting skills [1–5]. Usually, in colleges and schools the time allocated to perform experiments in the laboratory is insufficient to complete all the tasks in different scenarios, leading to underdeveloped laboratory skills and shallow conceptual understanding of the physics concepts involved in the experiment [6]. With the advancement and spread of information technology and an increasing interest of students in online learning components, one can hope that online laboratories such as a virtual laboratory or a remote-controlled laboratory [7–12] can supplement traditional laboratory techniques fruitfully. In this paper, we limit ourselves to the exploration of a virtual laboratory alone.

A virtual laboratory is an e-learning tool wherein software simulates the experiment and the learner follows a path of *discovery-based learning* rather than that of *verification-based learning*. Since this tool is a reusable object one can repeat an experiment several times and can visualize how changed parameters and settings affect the result in different possible scenarios, thereby allowing one to learn from his/her own explorations, overcoming the non-availability of apparatus. Furthermore, it opens up opportunities to perform inaccessible experiments that would usually require expensive and elaborate equipment/infrastructure (for example, a nuclear reactor, a Van de Graff generator, etc.) not possible in schools and colleges.

The Ministry of Human Resource Development (MHRD), Government of India, which looks after education as a whole in the country, has launched a comprehensive scheme utilizing information and communication technology for education, titled the *National Mission on Education through Information and Communication Technology* (NME-ICT). A key component of the NME-ICT is the creation, implementation and widespread use of virtual laboratories in colleges and universities as learning tools to support undergraduate, post-graduate, engineering, and science curricula. It is an effort to enhance, supplement, and in some cases replace real-world laboratory experiments [13].

Under the NME-ICT project, Amrita Vishwa Vidyapeetham, a private university, has developed virtual labs for physical sciences, chemical sciences, biotechnology and engineering under the NMEICT project. A complete list of virtual experiments developed in physics is available on the website of Amrita Vishwa Vidyapeetham [14]. The Millikan's oil drop (MOD) experiment is one of the experiments listed in the category of physical sciences.

The MOD experiment is a classical modern physics experiment to study the quantization of charge of an electron. Performing this experiment in the laboratory requires excellent hands-on skills. It requires a student to manage various parts of the equipment simultaneously to keep a charged oil drop in the field of view, which involves balancing of the downward gravitational force with the upward buoyant and electric forces on a tiny charged oil droplet selected from a spray of droplets suspended between two metal electrodes.

Furthermore, a learner has to control the motion of a selected drop to record observations. Moreover, viewing the chosen oil drop becomes a very tiring process and puts the conceptual understanding of this phenomenon on the back burner, leaving the learner in a fatigued scenario. However, by performing this experiment in a virtual lab one can easily comprehend the forces affecting oil drops. The MOD virtual experiment offers the following features:

- It provides a simulated view of the apparatus with control panels to facilitate the performance of the experiment.
- It provides a magnified view of the chamber.
- It provides visualization of the fall of oil droplets as a function of applied voltage.
- It provides a possibility of measurement of the rate of fall/rise of the drop between the cross-wires using a timer.
- It provides a virtual facility of x-rays to ionize air and to see the impact of their energy on the charging of the oil droplets.
- It provides repetition of the experiment by using parameters for olive oil and glycerin to see the effect of viscosity on the charge of the oil droplets.
- Above all, this virtual experiment is a reusable object and can be used any time, anywhere using a mobile/laptop/notebook.

This paper presents a study impact on learning outcomes of performing the MOD experiment using a virtual lab along with a perception survey. Multiple-choice questions, in the form of a well-defined pre-test and post-test, are put to use for this purpose.

2. Historical overview

In 1897, an English physicist, J J Thomson, discovered that the atom has an elementary negatively charged particle as its constituent called the electron. He measured its charge to mass (e/m) ratio, also known as a specific charge. Initially he and his students tried to calculate the fundamental electric charge using charged water droplet clouds falling under the influence of gravity and an electric field [15]. However, as the water clouds evaporated very fast, this method gave them a crude estimate of electronic charge. In this scenario, it was a challenging task to measure the charge on an electron accurately. In 1909, American physicist Robert Millikan and his graduate student Harvey Fletcher looked for a suitable liquid which could be converted into a spray of droplets and would not evaporate as fast as water clouds. They performed this classical experiment by using the highest grade of clock oil droplets produced from a small perfume atomizer ionized by x-rays. He published the result of performing this experiment on 58 droplets in 1913, showing that electronic charge is an integral multiple of the fundamental units of charge 1.5924×10^{-19} coulomb [16]. With Millikan's experiment, another proof about the existence of subatomic particles was firmly established and was accepted across the scientific world. This experiment is difficult to perform in the laboratory, since it requires a lot of coordination for the handling of various parts of the equipment. Moreover, the apparatus used is also expensive. A number of studies have been made to improve upon Millikan's procedure [17–20]. As an alternative to the traditional setup, a realistic computer-based simulator to replicate the MOD has also been developed [14] as a cheap reusable alternative and serves as the virtual apparatus for this study.

3. Research questions

To see the efficacy of the virtual apparatus available to students via the web, the following research questions were posed in this study:

i. Are virtual labs effective in learning physics concepts and procedure to perform the experiment?

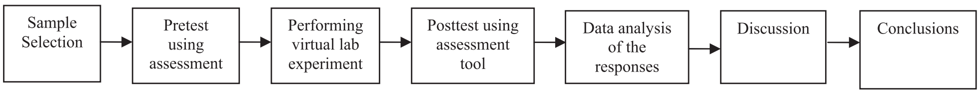


Figure 1. Sequential research design for a typical virtual experiment.

ii. Are there any learning gains as a result of performing a virtual experiment?
iii. What is the perception of the students who perform the MOD experiment using the virtual lab?
iv. Can virtual lab experiments replace real-world lab experiments?

4. Sample and methodology used

The sample group consisted of 41 students of the physics major, studying in the Bachelor of Science (BSc) degree course at St Bede's College Shimla, India. A summative assessment tool consisting of eight multiple-choice questions was designed (appendix A) in such a way that the questions touch the physics concepts involved in the MOD experiment, namely notion of charge, forces acting on a falling body in the presence of gravitational, electric and viscous force (because of the medium), and discretization of charge. This tool was administered to students as a pre-test and post-test, spread over a period of two laboratory sessions each of two hours duration. The following two steps were performed in this whole process.

Step 1: First, the theory and procedure of the MOD experiment were explained by the traditional 'chalk and talk' methodology in a typical classroom setting to the sample group. After this, the group took the abovementioned assessment test in the form of a pre-test.

Step 2: In the next step, the same group of students performed the MOD experiment in the virtual lab environment and recorded the readings. This was followed by the same assessment in the form of the post-test. Figure 1 shows the sequential research design for the experiment.

5. About the experiment

The following learning objectives of the MOD experiment were set:

After performing the experiment, the students should be able to

i. understand the theory of the experiment including Cunningham's correction;
ii. explain the functions of various parts of the apparatus;
iii. find the terminal velocity of the drop in the virtual setup;
iv. plot the scatter diagram and histogram of calculated charge;
v. understand the concept of quantization of the electronic charge from the data gathered about the experiment; and
vi. determine the charge on a single electron.

5.1. Theory of the experiment

In the MOD experiment, the oil droplets are blown with the help of an atomizer charged by x-rays into a capacitor, whose horizontal plates are at a distance d apart. The charged oil drops in the region of the capacitor plates experience three different forces: *gravitational force* F_g because of the pull of the earth, *electrical force* F_e because of the electric potential applied

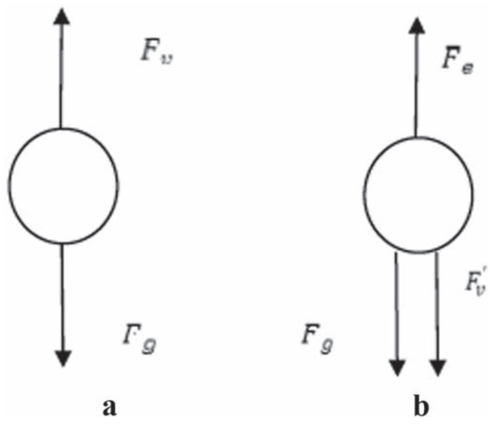


Figure 2. (a) Forces in the presence of gravitational and viscous force alone with $V = 0$ between the capacitor plates. (b) Forces when the electric field is switched on, i.e. $V \neq 0$.

through the capacitor plates, and *viscous force* F_v because of the medium in which the drops fall.

If the mass of the drop (assumed to be spherical) is m, the radius is r and the density ρ, then the gravitational force experienced will be $mg = \frac{4}{3}\pi r^3 \rho g$. As the drop is floating in air with density, it experiences an upthrust $U = \frac{4}{3}\pi r^3 \sigma g$. The resultant downward force is $F_g = \frac{4}{3}\pi r^3 (\rho - \sigma) g$.

Also, because of the motion of the drop in the air medium, the oil drop is acted upon by a retarding viscous force given by the famous Stokes law $F_v = 6\pi\eta r v_1$, where η is the viscosity of air, r is the radius of the drop and v_1 is the instantaneous velocity of the drop, as shown in figure 2(a). The velocity of the drop increases until terminal velocity is achieved, which occurs when

$$F_g = F_v \text{ or } \frac{4}{3}\pi r^3 (\rho - \sigma) g = 6\pi\eta r v_1. \tag{1}$$

When the electric field between the parallel plates, separated by a distance d, is switched on, by applying a potential difference of V, the uniform electric field produced between the plates is given by $\frac{V}{d}$. If the applied electric force F_e is greater than the downward forces, the charged drop starts to rise with terminal velocity v_2. Now the electric force will act upwards, gravity and viscous forces downwards, as shown in figure 2(b). The resultant balance of the forces becomes

$$F_e = qE = F_g + F_v'. \tag{2}$$

Using equation (1):

$$\begin{aligned} qE &= 6\pi\eta r v_1 + 6\pi\eta r v_2 \\ q\frac{V}{d} &= 6\pi\eta r (v_1 + v_2) \\ q &= 6\pi\eta r (v_1 + v_2)\frac{d}{V}. \end{aligned} \tag{3}$$

q is then calculated and found to be a multiple of charge on an electron, i.e. 1.6×10^{-19} C.

5.2. Deviation from Stokes law: Cunningham correction

Because of the motion of the oil drop is in a viscous medium, air, a retarding force acts governed by the Stokes law. Stokes law assumes that in a continuous medium the relative velocity of the air precisely at the oil drop surface is zero. However, if the oil drop gets smaller than 15 micrometers, the drag force decreases and the velocity of the oil drop increases, thus introducing a deviation in the Stokes law. There is an empirical way to correct this deviation suggested by Cunningham. Millikan applied this correction to his own data also. The formula for the corrected value of the charge is based on the observed radius of the drop (R) taken in μm and is given as [21, 22]

$$q_{corrected} = \frac{q}{\left(1 + \frac{0.077\,76\ \mu\mathrm{m}}{R\mu\mathrm{m}}\right)^{\frac{3}{2}}}. \tag{4}$$

6. Virtual performance of MOD experiment and learning outcomes

The virtual instrument (VI) for the above experiment was available as a web interface at the Virtual and Accessible Laboratories Universalizing Education (VALUE @ Amrita) Virtual Labs Project [14] website. Each student performed the MOD experiment as a virtual lab assignment. In addition to the instructions given by the instructor, using the 'chalk and talk' method, students were advised to read the background information and procedure provided in the e-text with the simulation. Students were advised to follow each step to perform the virtual experiment as shown in figures 3(a)–(c) and gather the relevant data in a tabular form already provided in the simulated environment as shown in figure 3(d).

- Students performed the experiment and calculated the value of the charge for 50 oil droplets, presented in an ascending order in the table given in (appendix B).
- Since the calculated radius of the oil drop was between 1–2 μm, the Cunningham correction was applied to get the corrected value of the charge.
- The scatter plot and histogram were plotted in an Excel spreadsheet.

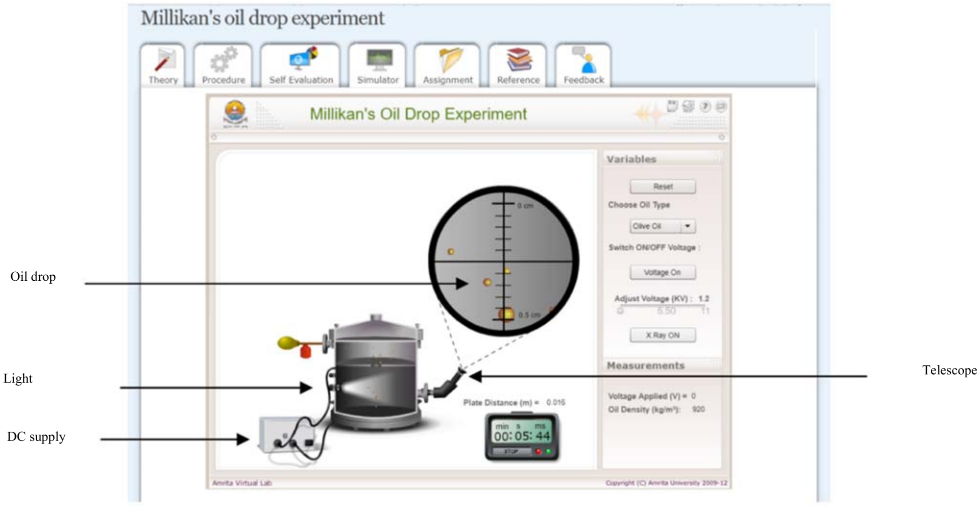
Figure 4(a), the scatter plot of the corrected electric charge, shows that the charges of these oil droplets are clustered around integer multiples of the elementary charge. Figure 4(b) shows the histogram of the charges obtained and demonstrates that the electric charge comes in discrete units indicating quantization of charge.

7. Implementation of summative assessment tool

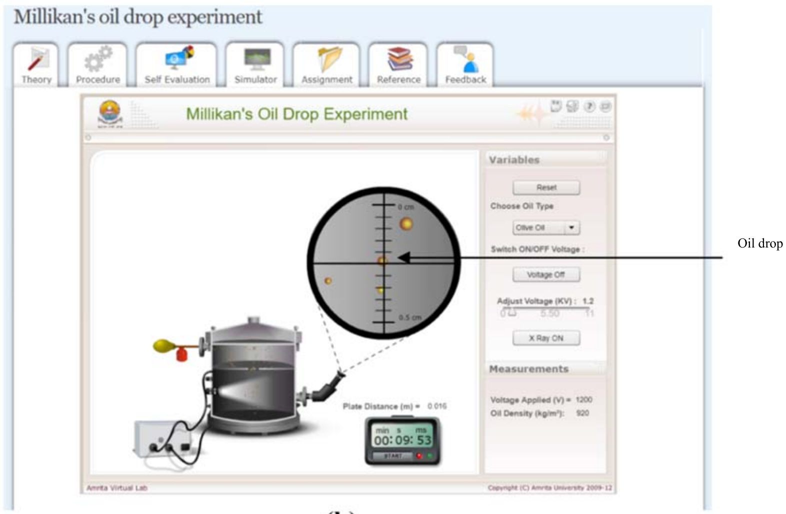
As mentioned above, a summative assessment tool consisting of eight questions was designed using different resources [23–25]. The face validity of the tool was established by having it reviewed by two different groups of teachers (that is, experts) to ensure that the questions were based on the topic of the MOD experiment and did not contain common errors. The tool was then administered to check the conceptual understanding of the students, in the form of pre- and post-tests.

7.1. Pre- and post-test comparison

Figure 5 shows a comparison of the percentage of students responding correctly to each question in the pre-test and post-test. The figure also displays the error bars with 5% value.



(a)



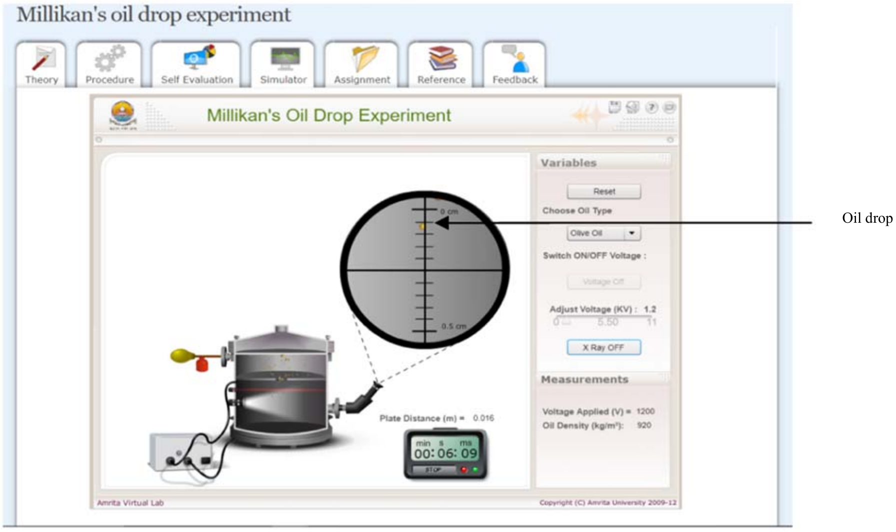
(b)

Figure 3. (a) Screenshot when no voltage is applied and oil drop is falling down. (b) Screenshot when a voltage of 1200 V is applied to balance the oil drop. (c) Screenshot when x-ray is switched on and drop starts moving in upward direction. (d) Virtual lab simulation screenshot of worksheet. Reproduced from http://vlab.co.in/index.php. CC BY 3.0.

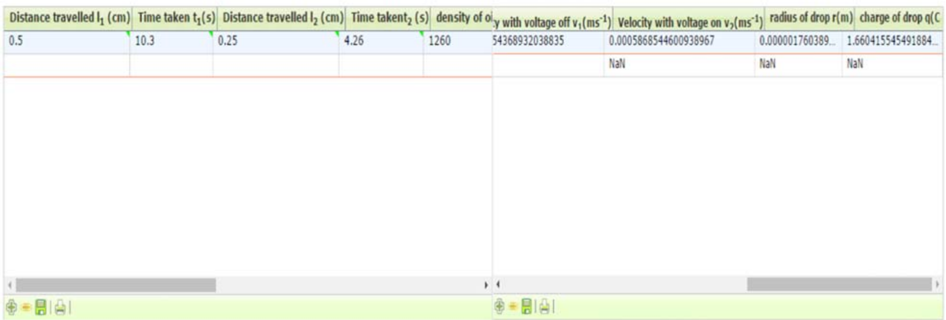
7.2. Normalized gain

The question wise normalized gain (g) using the formula given below was calculated [26, 27], to observe the improvement in the conceptual understanding of the MOD experiment by the students:

$$g = \frac{(\%posttest - \%pretest)}{(100 - \%pretest)}.$$



(c)



Distance travelled l_1 (cm)	Time taken t_1(s)	Distance travelled l_2 (cm)	Time takent_2 (s)	density of oi	y with voltage off v_1(ms^{-1})	Velocity with voltage on v_2(ms^{-1})	radius of drop r(m)	charge of drop q(C
0.5	10.3	0.25	4.26	1260	54368932038835	0.0005868544600938967	0.000001760389...	1.660415545491884...
						NaN	NaN	NaN

(d)

Figure 3. (Continued.)

The result obtained is given in table 1.

Using the criteria established by Hake [27] for the interpretation of gain, we found that in Q1, Q4, Q5, Q6 and Q7 there was a low normalized gain (<0.3) but in Q8 the normalized gain was medium ($g < 0.7$). The t-test for two paired sample/two-tailed test, performed in Excel, gave the p-value 0.013 (<0.05), which means the gain so obtained was significant. A typical interpretation of these normalized gains reflects the students' improvement in conceptual understanding of the MOD experiment.

8. Analysis and discussion

8.1. About MOD experiment

Figure 5 illustrates that the students' performance was improved in post-test. The normalized gain obtained is shown in table 1.

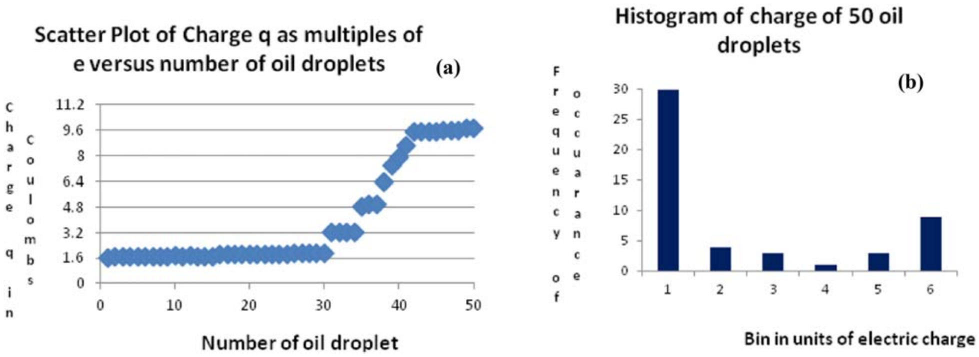


Figure 4. (a) and (b) Inferences about quantization of charge through scatter plot and histogram: a spreadsheet view.

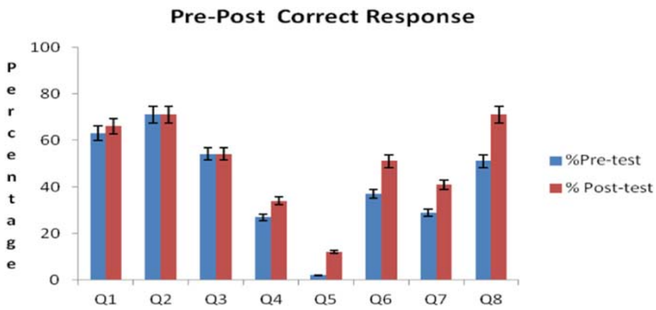


Figure 5. Percentage of students responding correctly for each question on the pre-test and post-test.

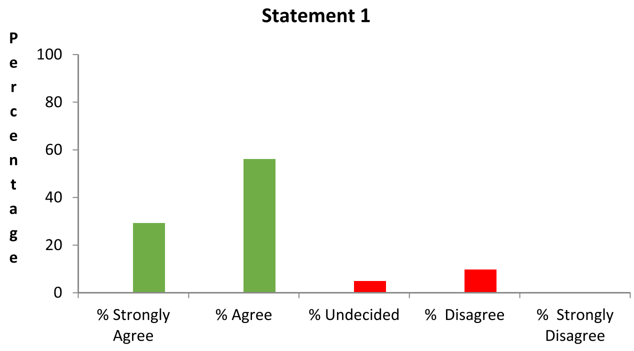
Table 1. Question wise normalized gain.

Question No.	%Pre-test	% Post-test	Gain
1	63	66	0.08
2	71	71	0
3	54	54	0
4	27	34	0.1
5	2	12	0.1
6	37	51	0.22
7	29	41	0.17
8	51	71	0.41

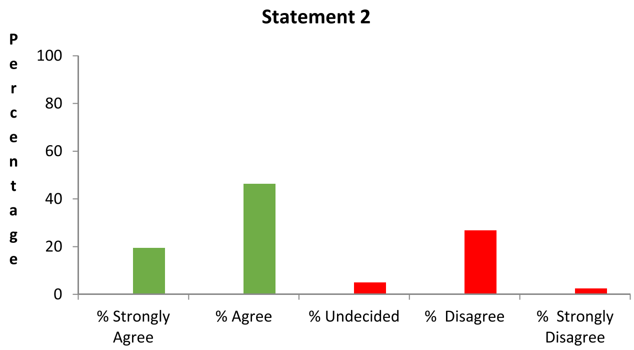
In Q1, it was asked that, if we replace negatively charged oil droplets by positively charged oil droplets, what would happen to the magnitude of charge on them. Sixty-three percent of students gave a correct response (option a) in the pre-test, which further increased to 66% in post-test with a normalized gain of 0.08, after the performance of the VL experiment.

Q2 was based on the relationship of the size of the droplet and charge carried by it. For this question, the percentage of correct responses remained the same both in pre-test and post-test.

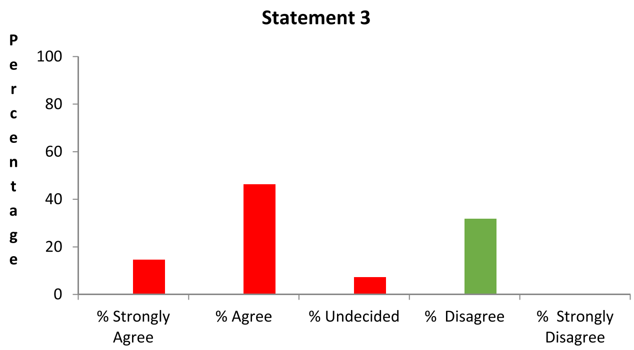
Q3 and Q4 were based on the concept of the direction of the electrostatic force exerted on the droplet. In Q3, the percentage of correct responses remained the same both in pre-test and



(a)



(b)



(c)

Figure 6. (a) Bar chart showing the response of the population set, for statement 1: I think I learned more physics concepts by participating in virtual labs. (b) Bar chart showing the response of the population set for statement 2: I think I learned more about how to perform physics laboratory procedures in virtual labs. (c) Bar chart showing the response of the population set for statement 3: I think I learned more about how to use physics laboratory equipment participating in virtual labs. (d) Bar chart showing the response of the population set for statement 4 : I think virtual labs are less time consuming. (e) Bar chart showing the response of the population set for statement 5: I prefer to participate in virtual labs. (f) Bar chart showing the response of the population set for statement 6: I think virtual labs can replace real experimental (traditional) labs.

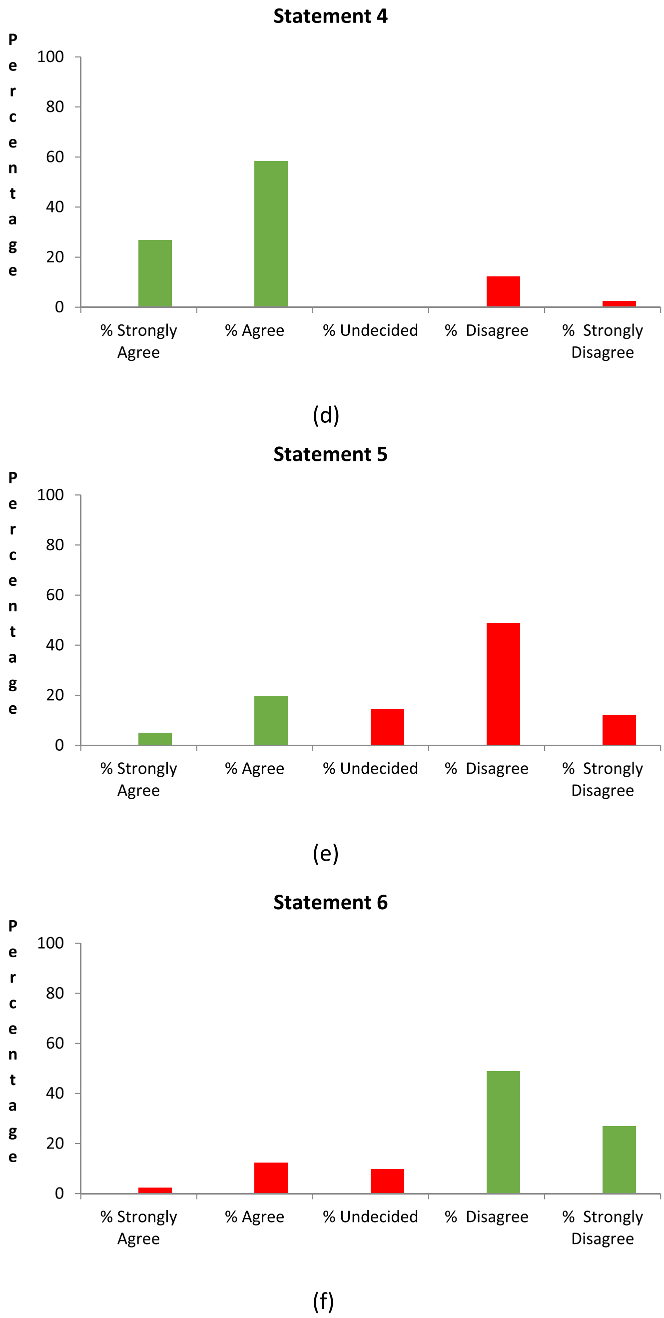


Figure 6. (Continued.)

post-test. In Q4, the percentage of correct responses was 27% in pre-test and increased to 34% in post-test after the performance of the experiment, showing a gain of 0.1

Q5 was on the quantization of the charge. Very few students (only 2%) gave the correct response (option d) in the pre-test. However, after performing the experiment, at least 12% of students gave the correct response with a normalized gain of 0.1.

Q6 was on the relationship between the three forces acting on an oil drop falling with uniform velocity, namely the electrical force F_e, the gravitational force F_g and the viscous force F_v. In this question the percentage of correct responses increased from 37% in pre-test to 51% in post-test, with a gain of 0.22.

Q7 and Q8 were two pictorial questions based on the concept of discretization. In both the questions there was an increase in the percentage of correct responses from pre- to post-test, showing a normalized gain of 0.17 and 0.41, respectively.

8.2. About perception survey

The students' perceptions of using a virtual lab were also gauged using a perception survey, which was based upon six statements on a five-point Likert scale, from 1 (strongly disagree) to 5 (strongly agree). Students completed this survey anonymously at the end of their virtual laboratory experiment performance. Responses are illustrated by bar graphs in figures 6(a)–(f). In each of these figures, perceptions were converted into a percentage by dividing the student response numbers for each statement by a total number of responses. The students' perceptions were also compared with the responses of five experts (shown in green color in figure 6 and appendix C), who were given a demonstration of the MOD experiment in the virtual lab.

From the responses of students on the perception survey, one can conclude that, overall, the use of a virtual lab has benefited them in conceptual understanding. The students revealed that they have learned concepts better and could perform the experiment with more clarity of procedure by participating in the virtual lab, as they could repeatedly do it conveniently. They also reported that they had enjoyed the virtual laboratory, as it was user friendly and less time consuming. The experts were also of the same opinion. However, some of the students revealed that they would like to work in a traditional lab as well, to learn how to use lab equipment and to touch and feel the apparatus. Our experts also had the opinion that it is difficult to learn the use of physics laboratory equipment by participating in virtual labs: they were of the opinion that the teachers in the classrooms should not use the virtual lab as a substitute for hands-on lab experiments. Some students mentioned that they needed the assistance of a teacher when they faced difficulties and doubts in performing the experiment.

9. Conclusions

The use of technology can take up the role of a good demonstrator in the physics laboratory to provide a complete understanding of the procedure of the experiment as well as grasping the concepts involved in it. The graphical representations and simulated environments have not only enhanced the visualization of a scientific phenomenon that was otherwise invisible to students but also influenced their comprehension. In this study of the performance of the MOD experiment in the virtual lab, the results obtained have been discussed by comparing the pre-test and post-test scores of students of the participating group. For each research question, the following can be concluded:

- *Are virtual labs effective in learning physics concepts and procedure to perform the experiment?*

From the pre-post test comparison, it is evident that students have shown a normalized gain in their score in a summative assessment tool administered to them. Moreover, through the perception survey it is clear that majority of the students have agreed that they have learned more physics concepts by participating in the virtual lab. They have also investigated what will happen to the value of charge if they replace oil with olive oil or glycerin; this comparison was not possible to see in a real laboratory so conveniently. Thus, a properly designed simulation can act as an effective educational tool in creating student interest in real equipment and in enhancing their conceptual understanding.

- What is the perception of the students who perform the MOD experiment using the virtual lab?

- Through the perception survey, we found that, overall, the feedback of students was encouraging as they felt that the use of virtual laboratories has increased their motivation, facilitated their self-learning attitudes, enhanced theoretical understanding, and has acted as a pre-real laboratory demonstrator.

- One important issue that crops up in this study is that computer simulations alone do not seem to be sufficient to properly train the students to use specific laboratory equipment. Instead, traditional labs are found to be more effective pedagogical techniques in terms of teaching them how to use physics lab equipment.
  - Can virtual lab experiments replace real-world lab experiments?
  Virtual lab simulations can be used to bridge the digital gap and to teach the experiments using the internet, as they are more efficient and less expensive. They can replace real lab experiments in situations where
- the institutions cannot afford some of the equipment due to their cost;
- access to real lab equipment is not commonly available especially in remote areas; and
- students want to learn at their own pace, at their own convenient time and place of their own choice.

We conclude that a virtual instrument of the experiment can be used either prior to or during a hands-on experiment in the same way as pilots are trained to fly aeroplanes on a simulator before actual flight runs. This can enable students to understand what they have to do and why they are doing it. This approach can help the student perform a more comprehensive analysis of the theory and gain a better understanding of the relevance of the topic to be learned, thereby allowing them opportunities to have multi-representation learning and filling in the gaps missed during lectures and textbooks. Thus, we can conclude that if virtual lab experiments are blended with hands-on experimentation they have the potential to raise students' motivation for learning and strengthen their understanding of the basic physical concepts taught in the classrooms, by relating theoretical concepts to real-world examples. However, the virtual lab cannot replace teachers in the classroom, as students always need their assistance during the performance of the experiments.

Acknowledgements

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Appendix A

Pre-Post Test Multiple Choice Questions

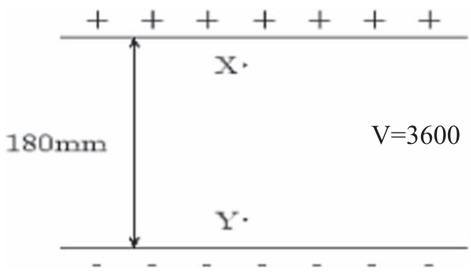

Figure A1. Two charged parallel plates with a given potential difference and separated by the given distance.

Q1: In Millikan's oil drop experiment, if instead of negatively charged droplets, we take positively charged oil droplets, the magnitude of charge on them will

a. remain same
b. increase
c. decrease
d. first decreases then increases

Q2: Which statement is true According to Millikan's oil drop experiment?

a. large droplet carries a large charge
b. fast droplet carries a large charge
c. slow droplet carries a large charge
d. all droplets have the same charge

Q3: Two charged parallel plates are at a distance of 180 mm from each other. The potential difference between them is 3600 V, as shown in the figure A1.

If a small oil drop of negligible mass, carrying a charge of $+6.8 \times 10^{-9}$ C, is placed between the plates at point X, the magnitude and direction of the electrostatic force exerted on the droplet.

a. 1.36×10^{-4} N upwards
b. 1.36×10^{-4} N downwards
c. 2.44×10^{13} N upwards
d. 2.44×10^{13} N downwards

Q4: In the above figure A1 If the droplet is now moved to point Y, the force exerted on it will be

a. more
b. less
c. remains the same as in Q3
d. cannot be defined

Q5: Which of this value of electric charge is unlikely in Millikan's oil drop experiment?

Figure A2. The right image image (Vending machine coffee) has been obtained by the author(s) from the Wikimedia website, where it is stated to have been released into the public domain. It is included within this article on that basis.

a. 3.2×10^{-19}
b. 1.6×10^{-17}
c. 8×10^{-18}
d. 5.6×10^{-19}

Q6: In Millikan's oil drop experiment, three forces act on the oil drop falling with uniform velocity namely electrical force F_e, gravitational force F_g and viscous force F_v? Which one of the following options is true?

a. $F_e + F_g = F_v$
b. $F_e > F_g + F_v$
c. $F_g > F_e + F_v$
d. $F_e + F_g + F_v \neq 0$

Q7: Characteristic of discrete values is that the suited value may not assume any possible value but only certain discrete ones. Three examples from everyday life, technique and from mathematics are: staircase (width of steps 20 cm, height of steps 10 cm), vending machine (Cola 1 €, water 0.8 €, mix drink 1.3 €) in figure A2 and series of numbers $f(n) = \frac{1}{n}(n \in \mathbb{N})$.

Specify in which case value is discrete in these examples

a. staircase value
b. vending machine value
c. number series value
d. all

Q8: In the above question, the difference of the discretization is constant in

a. staircase value
b. vending machine value
c. number series value
d. none

Appendix B

Determination of charge q of the 50 oil droplets

S. No	Radius of drop in μm	Charge x10^{-19} (C)	Balancing Potential (V)	Corrected Charge x10^{-19}(q)	q/e
1.	5.4	1.59	10 800	1.6	1
2.	2.27	1.50	1000	1.71	1
3.	3.49	1.61	3000	1.72	1
4.	5.59	1.67	10 700	1.72	1
5.	3.49	1.62	2900	1.73	1
6.	2.27	1.53	1000	1.73	1
7.	2.79	1.58	1600	1.73	1
8.	2.49	1.56	1100	1.74	1
9.	3.15	1.63	2300	1.75	1
10.	2.31	1.56	1100	1.75	1
11.	4.4	1.69	5000	1.76	1
12.	3.7	1.66	3000	1.76	1
13.	4.46	1.70	5200	1.78	1
14.	2.36	1.60	1000	1.79	1
15.	3.7	1.70	3000	1.80	1
16.	2.39	1.61	1000	1.80	1
17.	2.4	1.62	1000	1.81	1
18.	2.41	1.63	1300	1.81	1
19.	2.31	1.64	1000	1.83	1
20.	2.38	1.66	1000	1.84	1
21.	2.22	1.65	800	1.86	1
22.	2.42	1.68	1000	1.87	1
23.	2.38	1.69	900	1.88	1
24.	2.41	1.69	1000	1.88	1
25.	3.72	1.80	3000	1.90	1
26.	2.37	1.76	900	1.95	1
27.	2.96	1.82	3000	1.96	1
28.	2.96	1.82	3000	1.96	1
29.	2.96	1.82	1000	1.96	1
30.	1.51	1.59	800	1.97	1
31.	3.87	3.06	1700	3.16	2
32.	3.32	3.06	1200	3.18	2
33.	1.52	2.83	900	3.20	2
34.	2.09	2.99	5100	3.21	2
35.	1.27	4.38	1100	4.87	3
36.	2.5	4.84	1000	5.02	3
37.	1.78	4.73	1300	5.02	3
38.	1.78	6.21	1300	6.50	4
39.	1.83	7.14	1200	7.41	4
40.	4.53	7.82	1100	7.89	5
41.	5.27	8.59	1200	8.65	5
42.	4.38	9.39	10 600	9.47	6
43.	2.08	9.25	1400	9.49	6
44.	2.07	9.26	1400	9.49	6
45.	2.15	9.31	1200	9.53	6
46.	2.17	9.78	1200	9.6	6

(Continued.)

S. No	Radius of drop in μm	Charge x10^{-19} (C)	Balancing Potential (V)	Corrected Charge x10^{-19}(q)	q/e
47.	2.35	9.45	1700	9.64	6
48.	2.09	9.44	1200	9.67	6
49.	2.18	9.51	1200	9.72	6
50.	2.07	9.51	1200	9.74	6

Appendix C

Experts' responses on perception survey (marked in green).

S. No	Statements and Response				
1	I think I learned more physics concepts by participating in virtual labs				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**
2	I think I learned more about how to perform physics laboratory procedures in virtual labs				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**
3	I think I learned more about how to use physics laboratory equipment by participating in virtual labs				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**
4	I think Virtual labs are less time consuming				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**
5	I prefer to participate in virtual labs				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**
6	I think Virtual labs can replace real experimental (traditional) labs				
	Strongly Disagree	**Disagree**	**Undecided**	**Agree**	**Strongly Agree**

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