LOOK ACADEMIC PUBLISHERS
OPEN ACCESS

INTERNATIONAL JOURNAL OF ENVIRONMENTAL & SCIENCE EDUCATION
e-ISSN: 1306-3065
2019, Vol. 14, No. 4, 207-217

Examining the Implementation of PhET Simulations into General Chemistry Laboratory

Issa I Salame [1*], Danielle Samson [2]

[1] *The Department of Chemistry and Biochemistry and The School of Education, The City College of New York of the City University of New York, USA*
[2] *Department of Biology, The City College of New York of the City University of New York, USA*

* CORRESPONDENCE: isalame@ccny.cuny.edu

ABSTRACT
Traditional general chemistry laboratories are highly structured and used to verify concepts that are covered in the textbook or lecture. This practice is very different from a scientific investigation and is often referred to as "cookbook". This project aims to transform the traditional emphasis in general chemistry laboratory experiments from individual or paired "cookbook" exercises to an innovative approach. We also aim to further enhance student achievement by fostering problem-solving skills while incorporating the use of cybermedia in the form of PhET interactive labs and Excel program. Incorporating the use of internet-based technologies into chemistry laboratory improves students' problem-solving skills as well as adding relevance and interest to students' mastery of the content in the chemistry curriculum. Our method of data collection is a Likert-type and open-ended questionnaire, that was distributed at the end of each of the newly integrated labs into the General Chemistry I curriculum in an anonymous fashion. The collected data enabled us to examine the impact of implementing Excel, PhET interactive labs, and problem-solving session in General Chemistry I laboratory at The City College of New York. Overall, these experiments had a positive impact on the students' attitudes towards chemistry, contributed to the learning experience, increased their involvement in the topics, and complemented the traditional tabs.

Keywords: PhET interactive simulations, chemistry education research, laboratory and technology

INTRODUCTION

The discipline of chemistry has a long and winding history that has unequivocally provided current and future students with advantages to understand chemistry in ways that previous generations could have never imagined. In the last 200 years, laboratories have diverged from lectures as a separate venue allowing students to a gain hands-on, practical understandings of chemistry. While the initial purpose of developing laboratories was to generate skilled technicians for advanced technological work, today's aim has shifted as the majority of undergraduates taking a chemistry course do not end up as bench chemists. Today's general chemistry laboratories cover a series of introductory topics, and unlike the more advanced chemistry classes, these experiments are designed to teach novice students chemistry basics related to their lecture classes, but to also teach them an introduction to laboratory science equipment (National Research Council, 2005).

According to the American Chemical Society, students should be taught in an environment that is not only engaging but inclusive and that accommodates a wide variety of learning styles. Some examples of effective methods are problem-based learning, inquiry-based learning, peer-led instruction, group learning, and

Article History: Received 1 June 2019 ◆ Revised 19 July 2019 ◆ Accepted 19 July 2019

technology-aided instruction. The students using these "cookbook" laboratory manuals often follow written instruction mindlessly (Pickering, 1989) where the students' main goal for the lab is to complete the experiment (Berry et al., 1999). We should note that the collection of the data and manipulation of the data is crucial to the learning process (Monteyne & Cracolice 2004).

Even with all the tremendous outcomes that follow laboratory work, over the last century general chemistry laboratories have kept very similar practices and have very rarely altered their programs and methods. Unfortunately, the turn of the century brought along new technological advances that have led students to not only expect, but generally require high levels of stimulation to be fully engaged (Nevid, 2011). Laboratory classes are typically taught by graduate students who have little interest in teaching, and "cookbook" type experiments leave university students with negative attitudes and little interest in actually understanding the point of the exercises. The graduate students are often more interested in finishing their thesis projects than if their students fully understand the concepts that the experiments are designed to address. Instead of allowing the students to work through the experiments purposefully, the teaching assistants roam around the lab giving away answers freely and herding the students to stay on course. This leaves the students hurried to get through the procedures without fervor, a clear purpose or understanding. Universities are left uneasy as "traditional" laboratories no longer cater to the newer, unconventional millennials; thus, the lingering question remains, "are the students fully benefiting from the traditional laboratories?" (Winkelmann et al., 2017). Since the majority of the students do not move on to be lab technicians, are there ways to assist the newer generations with practical skills like problem-solving, data interpretation, and critical thinking? These higher-ordered thinking skills are of considerable value after graduation.

By having an active role in the laboratory, the students can dynamically partake in the experimental processes which will enable them to develop improved mental dexterity. Research shows that modern-day students are better able to comprehend complex ideas if they are engaged and involved in the process and have stimulating pedagogical approaches such as audio, video, and hepatic learning (Ullah et al., 2016). Relating science to real-life situations where students can visually see and manipulate experiments, are proving to be much more valuable than lecture-based learning (Barron & Hammond, 2008). Understanding the nature of science, scientific discourse as well as gaining skills with laboratory technology will help students access further research opportunities that may lead to careers in science.

Relevant laboratory computer skills also enhance career paths as students become curious in how the technology works. Having the ability to use software to plot a graph is also useful in many future courses. Learning to understand mathematical relationships in a graphic-based user-friendly manner helps students internalize basic mathematical skills and, most importantly, helps them understand why mathematical thinking is important in scientific endeavors. Microsoft Excel proficiencies are determined to be a necessity for future employment of current college students (Formby, 2017). One study reported that 78% of middle skilled jobs calls for Excel competency (Geiger, 2015). The Excel program has become an extremely valuable and ubiquitous tool for statistical analysis. Lack of basic understandings of the program would be detrimental to science students.

Virtual laboratories, like the Virtual General Chemistry Laboratory by the University of Colorado, Physics Education Technology (PhET), allow students to carry out laboratory experiments digitally that many schools may not have the physical facilities to conduct. These simulations are interactive, engaging, and allow student to explore and discover scientific concepts. The simulations are scientifically accurate, and offer highly illustrative, dynamic representations of principles of chemistry. They help students develop conceptual understanding of the topics. PhET simulations have been found to provide students in physics with more conceptual understanding than the textbook, traditional lab or live demonstration (Finkelstein et al., 2006). PhET simulations over the course of a semester provided participants with higher mastery of key physics concepts when compared to traditional labs (Finkelstein et al., 2005). These experiments enhance students' laboratory experiences.

The experiments incorporate an inquiry-based approach to learning, where students are encouraged to discover principles, properties, and relationships in realistic simulations. PhET simulations enhanced construction of knowledge in students and more meaningful understanding (Fund, 2007). The experiments use photographic images of real laboratory equipment that students can manipulate freely in the PhET interactive simulation environment. Through the use of animation, students can clearly see the relationships between variables such as temperature, pressure and volume of Gas Laws. The animation shows these relationships in an intuitive visual interface. It is much more difficult for most students to understand these relationships in numeric form. However, by gathering data from the PhET interactive simulations, virtual labs, as they see variables change, entering them in Excel program and then plotting the data as a graph, students will internalize the relationship between "real life" and the way Gas Laws are depicted through graphs and other mathematical representations.

While research from institutions such as the National Research Council and the National Science Education support the notion that conventional laboratories are no longer significant, there are several obstacles keeping universities from fully replacing traditional labs, like university accommodations and costs (Elliott et al., 2008). However, incremental changes could be a viable option for universities. A growing trend in general chemistry laboratories is virtual online experiments. These activities are allowing students to simulate what it is like to be an actual chemist whilst applying their knowledge from their textbooks and lectures. Due to low budgets, and high student capacity, available resources, and practical run-times experiments are now much less common, but the need is still relevant (Stone, 2007). These virtual online experiments allow students to plan, make decisions, and collaborate on ideas with their fellow students. These virtual labs are challenging enough to stimulate the students while simultaneously inspiring them with an engaging activity; and having outcomes that depends on the students' actions ensure realistic laboratory experience (Winkelmann et al., 2017).

The virtual lab is simply an additional tool to help the students fully comprehend the materials being taught in the lecture and physical laboratory. Virtual simulations aren't necessarily implemented in order to teach laboratory and practical techniques, but to make connections as to why the students are applying the knowledge and how they direct that knowledge to their lectures (Woodfield et al., 2005). More universities are leaning towards these virtual and online-based simulation and experiments because they affordably increase the students' exposure to accurate and life-like chemistry while also reducing university costs, and limiting exposure and elimination of hazardous wastes (Carnduff & Reid, 2003).

One reported finding is that students view the interactive simulations in a similar way that scientists views their research experiments, which is a crucial part of learning (Wieman et al., 2008). Scientists' and students' views include, enjoyable, explorative, and improves their understanding of research and PhET simulations, respectively. "They encourage authentic and productive exploration of scientific phenomena, and provide credible animated models that usefully guide students' thinking." (Wieman et al., 2008). Furthermore, PhET simulations have been found to significantly increase students' scientific creativity (Astutik & Prahani, 2018).

METHODS

In this study, we set out to integrate PhET interactive simulations as virtual labs and statistical analysis into the general chemistry laboratory, in the hopes of improving students' achievement and attitudes towards chemistry. In one study, researchers suggested that combining traditional bench labs with virtual labs enhanced research skills (Bortnik et al., 2017). Novice students should be provided with the tools, content, technology and strategies so they can better learn the complex materials more accurately to represent practicing scientists today. We hope to transform the traditional general chemistry laboratory experience from "cookbook" type experiments to innovative experience that can be discussed with peers and teaching assistants in a thought provoking manner that mimics communication within the scientific community. We further aim to enhance the students experience by fostering problem-solving skills with the use of internet-based technologies. Our hope is that this will improve their problem-solving skills whilst also enhancing their interest in science, engineering, and technology careers and mastering the general chemistry curriculum. We believe that learning sciences through engaging debates and discussions will lead to a more thorough understanding of the subject and gain integral skill-sets beneficial to life after college. Our research question is: How does the implementation of PhET interactive simulations, virtual labs, Excel program, and problem solving-sessions, impact students' attitudes and learning experience in General Chemistry Labs?

Several changes to the current curriculum will form a transformative approach to teaching the new generation of young college students. These changes include: integrating Microsoft Excel, statistical analysis, and PhET interactive simulation as a virtual lab. We have introduced two PhET interactive simulation - virtual labs, one Excel lab, and one discussion and problem-solving lab into General Chemistry I at the City College of New York. Our general chemistry course is offered to around 600 students per semester. After each of the newly integrated labs, a survey was distributed to the students, collected, analyzed, and evaluated.

The first lab that was introduced to the students serves as an introduction to Microsoft Excel lab. While often the goal of undergraduate science labs is to determine if an outcome is "statistically significant", we determined that implementing a block of time to teach the basics of Excel would be beneficial for the students. Understanding Excel is also extremely critical because this skill directly follows the students into the subsequent general chemistry II class where statistical analysis by excel is highly utilized. The lab teaches the aesthetic basics, how to function with rows columns and worksheets, how to format cells, basic formulas such as sum, date, average, count, and how to create charts.

The two PhET interactive simulations, virtual labs, that we have incorporated into our general chemistry curriculum are Gas Laws lab and a Spectroscopy lab. The virtual gas lab written by Anderson, D. R., & Syme, A. S at the University of Colorado. Gas laws are an important concept in general chemistry courses as they fundamentally provide the relationship between pressure, temperature, volume and amount of gas. The virtual simulation visually illustrates the differences between Boyles', Charles', and Guy-Lussac's laws. These cannot be performed in traditional labs due to cost and safety. Virtual labs or simulations allow student to perform an experiment that is otherwise not possible, such as dangerous chemicals, expense, or lack of equipment (Rodrigues, 1997). Using this specific concept as a virtual lab, PhET interactive simulation, allows the students to gain a virtual "minds-on" understanding of a rather difficult subject that would be inherently difficult to demonstrate in the physical lab itself due to safety concerns of the novice students. PhET interactive simulations improved learning of unobservable phenomena in chemistry when studying Le Chatelier Principle (Trey & Khan, 2008). This certainly applies to the Gas Laws.

The second PhET interactive simulation, virtual lab, that we introduced is a virtual pre-lab experiment for spectroscopy. Spectroscopy is the study of the absorption and emission of light and other radiation by matter, as related to the dependence of these processes on the wavelength of the radiation (Graybeal et al., 2017). In this virtual pre-lab simulation, we aim to help the students develop conceptual understanding of Beers' Law, through manipulation of visual spectroscopy.

As part of the evaluation and data collection process, the students were given questionnaires to fill out after they have completed the labs. This helped us quantify and analyze the impact of the newly integrated labs. The questionnaires also contained additional open-ended questions that provided us with relevant information about the implementation of the new labs.

RESULTS AND DISCUSSION

Approximately 700 surveys were collected and analyzed to determine the overall impact of the newly implemented labs. The students were briefed on the research project that they were involved in and we also explained the importance of their opinions and thoughts on the new materials; the students completed the surveys after the completion of each lab. The results stem from surveys collected during 2018/2019 academic year from general chemistry students. The data was collected with Likert-type and open-ended questions. The Likert-type questions we ranked from 1 to 5 where 1 is strongly disagree and 5 is strongly agree. For the open-ended questions that we collected, we used a rubric to give a value to each answer, also based on 5 point scale, where 1 represents a negative response and 5 represents a positive response.

Figure 1 shows the questions and averages that the students responded to for the Excel lab. The highest score was that the students generally believe having a basic understanding of Excel is important for their future endeavors. While the students seemed to have issues with the complexity of the instructions, they overall had a positive experience and would generally recommend the lab to future students. Students agreed that the Excel Lab was beneficial for their career advancement and that they enjoy using technology.

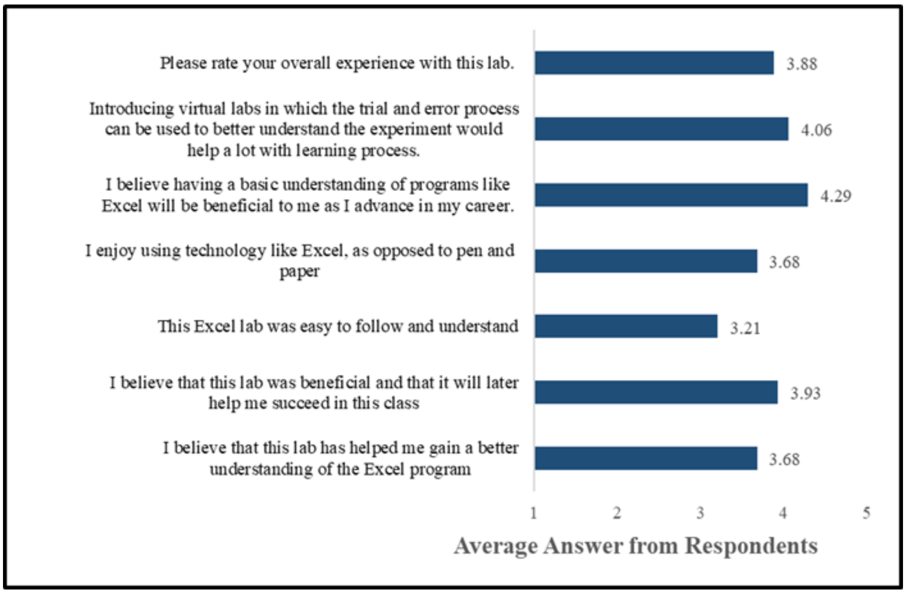

Figure 1. Likert-scale questions and averages that were given for the Excel lab

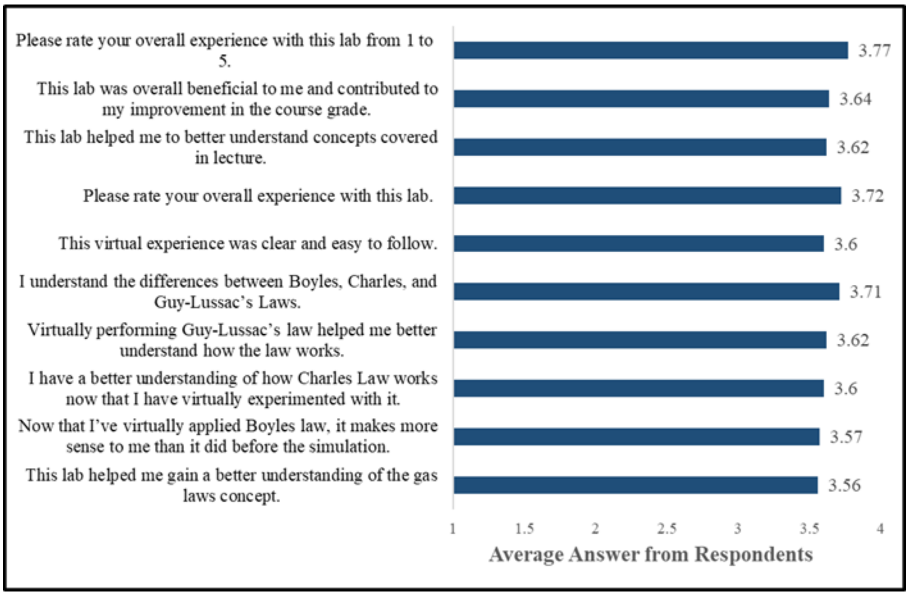

Figure 2. Likert-scale questions and averages for the Virtual Gas Laws Experiment

Figure 2 shows the average answers for the Likert-type questions from the students regarding the Virtual Gas Laws experiment. The overall experience was mostly fun and positive and students felt it did contribute to their overall understanding of the topics that were covered in their lecture and the differences between the various Gas Laws. A recent study suggests that virtual labs increased students' learning and improved problem-solving skills (Davenport et al., 2018). Additionally, data has shown that PhET simulations improve problem-solving skills for high school physics students (Wartono et al., 2017). Students agree that the PhET interactive simulation, Gas Laws virtual lab, increased their understanding and differentiating between the different Gas Laws, and contributed to an improvement in their overall learning and understanding.

Figure 3 represents the average answers from the students who participated in the virtual spectroscopy pre-lab experiment. The students had a positive experience with the lab and felt that it was an overall fun and valuable experience, they also felt like the virtual spectroscopy lab helped them gain better understandings of topics covered in lecture and develop a better understanding of Beers Law. Virtual labs can enhance conceptual learning (Trindade et al., 2002). Our data provides results that are consistent with other research in the area.

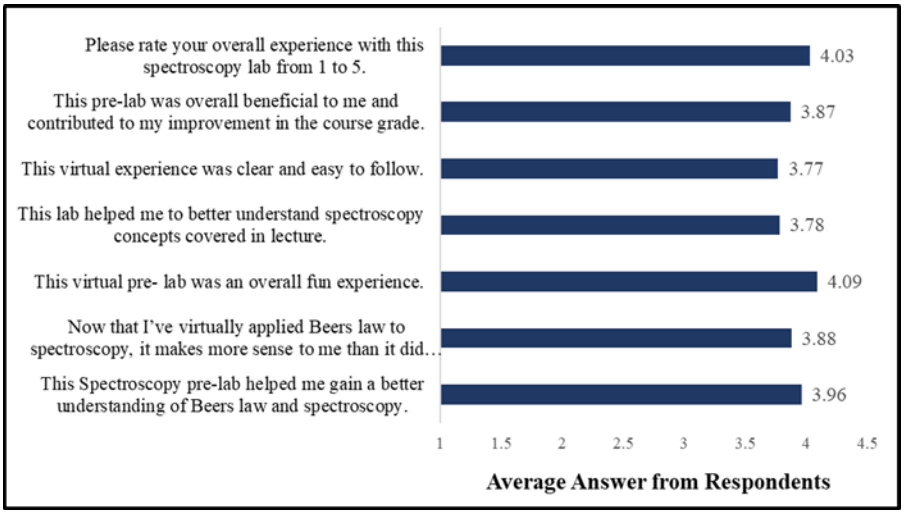

Figure 3. Likert-scale questions and averages for the pre-lab Virtual Spectroscopy Experiment

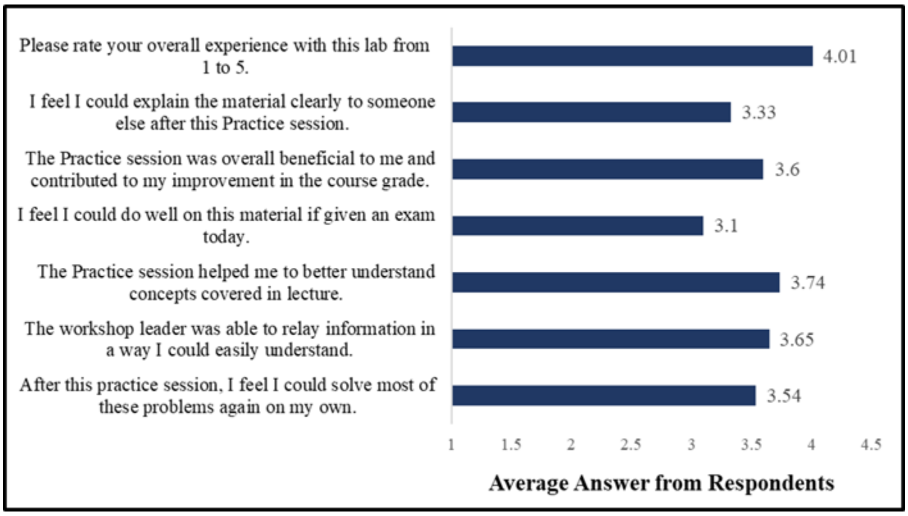

Figure 4. Likert-scale questions and averages for the Problem-Solving Session Experiment

Figure 4 shows the average responses given by students in regard to the problem-solving sessions with their workshop leaders. The students felt it was an overall valuable experience and that the workshop leaders did a good job helping them understand the difficult problems that could be seen on their exams. While the students were hesitant about being able to answer the practice problems on their own, they felt that the experience was important to the learning process.

Figure 5 shows the average answer from respondents for the open-ended question about the students' experience with the newly implemented labs. The students had an overall positive experience and would recommend using these labs for future general chemistry students. This is consistent with other research that suggests using Multimedia and virtual labs for teaching improves learning and increases students' success, as well as, students' feelings of competence towards the lesson (Limniou et al., 2007). Also, virtual labs are more enjoyable and attractive to students (Oloruntegbe & Alam, 2010). Some sample answers we received from students include:

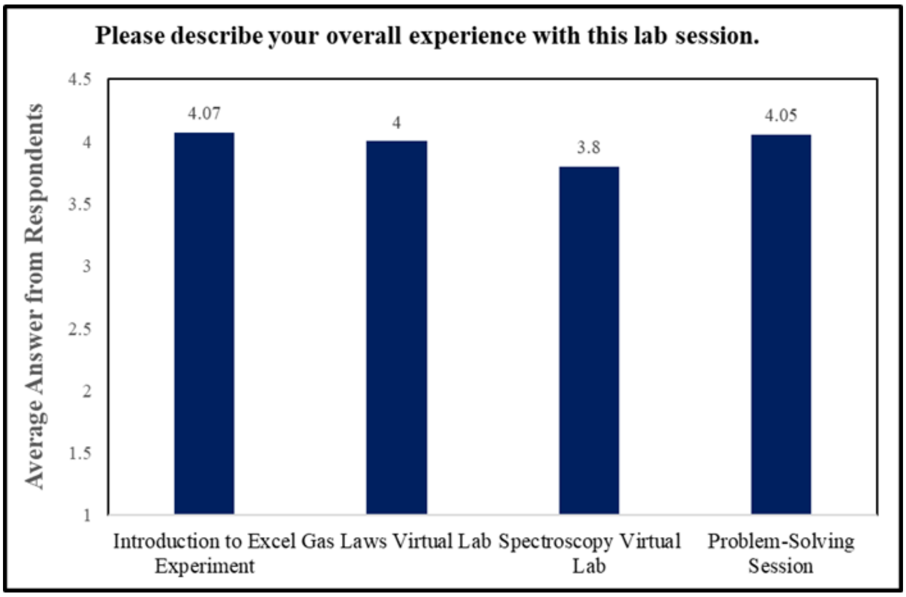

Figure 5. Short answer question and averages based on rubric used

Student 1: "*Instructions are clear an easy to follow and allowed me to visually see and understand Beers Law and spectroscopy*."

Student 2: "*It caught my attention more than being talked to. I rather do hands on work that's how I learn*."

Student 3: "*I struggle with chemistry but having visuals did help me understand what is happening*."

Student 4: "*It was fun and I enjoyed it and provided me with a better understanding of the overall concept/relationships*."

Our results are aligned with research data, on integrating models of hydrogen atom from PhET simulations, which show that students responded positivity in lab sessions to PhET interactive simulations and proved to be a valuable addition to introductory chemistry courses (Clark & Chamberlainm 2014). Furthermore, students were more involved in their own construction of knowledge and sense making.

The pie chart in **Figure 6** shows the concerns and issues we asked the students to bring to our attention regarding the newly implemented labs. The students stated that the Teaching Assistants weren't involved enough in explaining the labs and helping them through the process and that clearer instructions needed to be written (20.2%), and that the technical issues with the websites and the computers be fixed (19%), a few students needed more time (13.1%) or found it difficult to complete (10.7%), but overall (33.4%) of the students had no complaints and thought the new labs were fun helpful in the learning process.

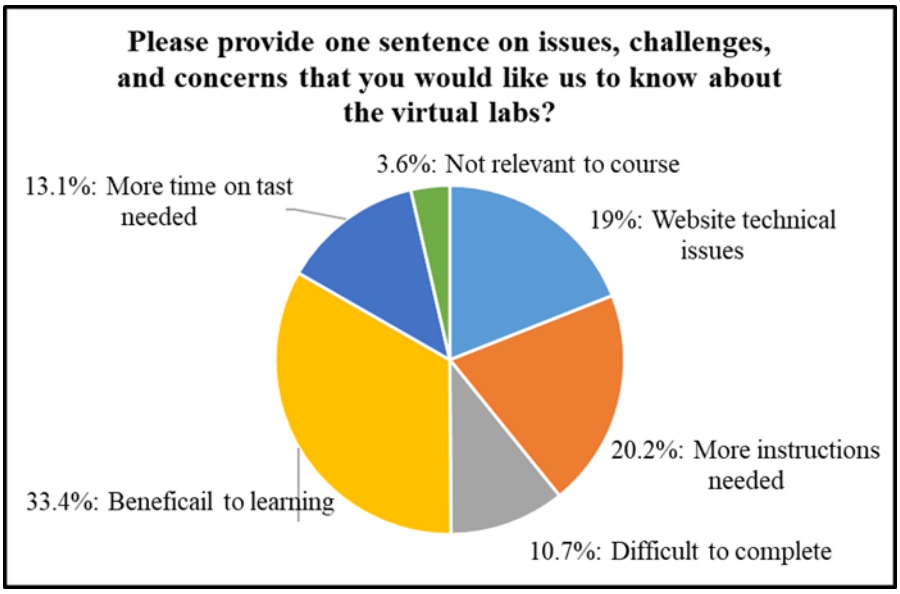

Figure 6. The pie chart above shows the issues, challenges, and concerns that students faced with virtual labs

The implementation of the four new labs demonstrated, generally, to be a successful and positive development to the general chemistry curriculum. Because the students were alternating between traditional "cookbook" labs and newly integrated labs, it provided a dramatic perspective for the students that allowed for more of a subjective opinion when filling out the surveys. The students voluntarily provided short answers for each of the surveys which supplied us with additional information on how to shape and reformat the new labs. The students generally felt that the new labs were beneficial to them and were a positive use of their time; they also felt that the new labs were directly pertinent to materials that they were learning in class and thought that working with the PhET interactive simulations, virtual labs, and practice sessions set them up for success for exams.

The Excel lab received an overall average likert-scale score of (4.07) from the students and the strongest consensus was that they believed that having an understanding in the Excel program would be beneficial for them in the long-term (4.29). In the short answers provided there were several remarks such as, "Knowing excel will be helpful for future classes," and "Previous classes had Excel work that I couldn't understand."

The PhET interactive simulation of the Virtual Gas Laws lab received an overall average likert-scale score of (4.0) from the students and the strongest consensus was that after performing the virtual lab they had a better understanding of the differences between the different gas Laws. Virtual labs have been found to have a positive impact on students' achievement and attitudes when compared to traditional lab settings, and improved student motivation (Tuysuz, 2010). Furthermore, Virtual labs provide students with the opportunity to learn by doing, while maintaining a no harm to students and affordable cost environment (Rajendran et al., 2010). The PhET interactive simulation of the Gas Laws lab is a perfect example of a lab that cannot be performed in traditional setting due to safety concerns and high cost.

The short answers provided by the students informed us that having a visual representation with variables they can manipulate helped them better understand the purpose of the material. Some students did have technical issues with the programs and also voiced that they wanted more interaction from the supervising teaching assistants. The students also found the program to be fun and a useful way to spend their time in the lab. During virtual labs, students can improve their conceptual understanding of complex chemistry concepts by observing molecular-level phenomena (Chiu et al., 2015). Additionally, virtual labs can be motivating and create a new learning experience that can support learning by enhancing cognitive tasks (Josephsen & Kristensen, 2006). PhET interactive simulation creates a new learning experience that involves molecular-level observations.

The pre-lab Virtual Spectroscopy Experiment received an overall average Likert-scale score of (3.8) from the students and the strongest consensus was that it was a fun and unique experiment to participate in. It seemed there were a few more technical issues with this particular lab and the students did voice some concern as to understanding the directions. An example of a short answer provided was: "The lab was more fun and interesting than most other labs." Virtual labs provide the student with the opportunity to repeat the experiment as many times as needed and change any variable they choose which might not be feasible in traditional lab sessions (Kearney & Treagust, 2001). Furthermore, virtual labs allow students to study abstract concepts and improve competencies in graphical analysis (Wieman & Perkins, 2005).

The problem-solving session lab received an overall average likert-scale score of (4.05) from the students and the strongest consensus was that it helped them understand the concepts in lecture and was an important way to study for the exam. While some classes had teaching assistants that seemed to be more invested in solving the problems than others, there was still an overwhelming agreement from the students that they would be interested in having additional problem-solving sessions for additional topics. Students wrote shorts answers most relating to the fact that the session is helpful for the exams and that they could break down the material seen in class and lab more slowly.

CONCLUSION

Our results provide evidence that incorporating Microsoft Excel, PhET interactive simulations - virtual labs, and problem-solving into the General chemistry lab positively impacts students' attitudes and contributes to an improved learning experience. Modifying and updating General Chemistry labs to reflect technologies transforms students' views of the lab, improves their interest in the subject matter, and enhances their learning. While there seems to be a trend of the teaching assistants not being involved enough in the new labs, we think it would be beneficial to add training sessions for the teaching assistants and answer any questions that they might have and state the expectations of their roles more clearly. Our results show that students benefited from the integration of virtual labs, PhET interactive simulations and found them more involving than the traditional labs.

The PhET interactive simulations combined with traditional wet labs have a synergistic effect on learning and conceptual understanding of general chemistry topics. Our results indicate that there is a need to update and modify general chemistry laboratories to reflect emerging technologies and reach students in their comfort zones. Additionally, these labs are cost effective and can allow for experiments that could otherwise be challenging to run. We will be modifying and reshaping the labs based on the students' feedback to further improve the quality of the students learning. Future studies are needed to compare traditional labs and the newly integrated labs and we would eventually tackle the general chemistry II laboratory curriculum and alter those labs as well.

ACKNOWLEDGEMENT

We would also like the thanks the City University of New York Coordinated Undergraduate Education (CUE) program for funding this work.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Issa I Salame – The Department of Chemistry and Biochemistry and The School of Education, The City College of New York of the City University of New York, USA.

Danielle Samson – Department of Biology, The City College of New York of the City University of New York, USA.

REFERENCES

Astutik, S., & Prahani, B. K. (2018). The practicality and effectiveness of collaborative creativity learning (CCL) codel by using PhET simulation to increase students' scientific creativity. *International Journal of Instruction, 11*(4), 409-424. https://doi.org/10.12973/iji.2018.11426a

Barron, B., & Hammond, L. D. (2008). *Powerful Learning: Studies Show Deep Understanding Derives from Collaborative Methods*. Retrieved from https://www.edutopia.org/inquiry-project-learning-research

Berry, A., Mulhall, P., Gunstone, R., & Loughran, J. (1999). Helping students learn for laboratory work. *Australian Science Teachers Journal,* (45), 27-31.

Bortnik, B., Stozhko, N., Pervukhina, I., Tchernysheva, A., & Belysheva, G. (2017). Effect of virtual analytical chemistry laboratory on enhancing student research skills and practices, *Research in Learning Technology,* (25), 1-20. https://doi.org/10.25304/rlt.v25.1968

Carnduff, J., & Reid, N. (2003), *Enhancing Undergraduate Chemistry Laboratories, Pre-Laboratory and Post-Laboratory Exercises, Examples and Advice,* Education Department, Royal Society of Chemistry, Burlington House, Piccadilly, London.

Chiu, J. L., Dejaegher, C. J., & Chao, J. (2015) The effects of augmented virtual science laboratories on middle school students' understanding of gas properties, *Computers and Education,* (85), 59-73. https://doi.org/10.1016/j.compedu.2015.02.007

Clark, T. M., & Chamberlain, J. M. (2014). Use of a PhET interactive simulation in general chemistry laboratory: Models of the Hydrogen atom. *Journal of Chemistry Education,* (91), 1198-1202. https://doi.org/10.1021/ed400454p

Davenport, J. L., Rafferty, A. N., & Yaron, D. J. (2018). Whether and how authentic contexts using a virtual chemistry lab support learning, *Journal of Chemical Education,* (95), 1250-1259. https://doi.org/10.1021/acs.jchemed.8b00048

Elliott, M. J., Stewart, K. K., & Lagowski J. J. (2008). The role of the laboratory in chemistry instruction, *Journal of Chemical Education, 85*(1), 145. https://doi.org/10.1021/ed085p145

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., Reid, S., & R. LeMaster, R. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physics Review Special Topics Physics Education Research, 1*(1), 010103. https://doi.org/10.1103/PhysRevSTPER.1.010103

Finkelstein, N. D., Adams, W. K., Keller, C. J., Perkins, K. K., & Wieman, C. (2006). High-tech tools for teaching physics: the physics education technology project. *MERLOT Journal of Online Learning and Teaching, 2(*3), 110-120.

Formby, S. K., Medlin, B. D., & Ellington, V. (2017). Microsoft Excel®: Is it an important job skill for college graduates? *Information Systems Education Journal, 15*(3), 55-63.

Fund, Z. (2007). The effects of scaffolded computerized science problem-solving on achievement outcomes: a comparative study of support programs. *Journal of Computer Assisted Learning, 23*(5), 410-424. https://doi.org/10.1111/j.1365-2729.2007.00226.x

Geiger, B. (2015). *Your Excel Skills Could Land You Your Next Job.* Retrieved from http://fortune.com/2015/03/06/microsoft-excel-jobs/

Graybeal, J. D., Hurst, G. S., Stoner, J. O. & Chu, S. (2017). *Spectroscopy.* Retrieved from https://www.britannica.com/science/spectroscopy

Josephsen, J., & Kristensen, A. K. (2006). Simulation of laboratory assignments to support students' learning of introductory inorganic chemistry, *Chemistry Education Research and Practice, 7*(4), 266-279. https://doi.org/10.1039/B6RP90013E

Kearney, M., & Treagust, D. F. (2001). Constructivism as a referent in the design and development of a computer program which uses interactive digital video to enhance learning in physics. *Australian Journal of Educational Technology, 17*(1), 64-79. https://doi.org/10.14742/ajet.1773

Limniou, M., Papadopoulos, N., Giannakoudakis, A., Roberts, D., & Otto, O. (2007). The Integration of a Viscosity Simulator in a Chemistry Laboratory Chemistry, *Education Research and Practice, 8(*2), 220-231. https://doi.org/10.1039/B6RP90032A

Monteyne, K., & Cracolice, M. S. (2004). What's wrong with cookbooks? A reply to Ault. *Journal of Chemical Education,* (81), 845-846. https://doi.org/10.1021/ed081p1559

National Research Council. (2005). *Committee on High School Laboratories: Role and Vision. America's lab report: Investigations in High School Science*; Washington, DC.

Nevid, J. (2011). *Teaching the Millennials.* Retrieved from https://www.psychologicalscience.org/observer/teaching-the-millennials

Oloruntegbe, K. O., & Alam, G., M. (2010). Evaluation of 3D environments and virtual realities in science teaching and learning: The need to go beyond perception referents, *Scientific Research and Essays, 5*(9), 948-954.

Pickering, M. (1989). Choosing to cookbook: Student choices of laboratory strategy. *Journal of Chemical Education,* (66), 1559-1560. https://doi.org/10.1021/ed066p845

Rajendran, L. Veilumuthu, R., & Divya, J. (2010). A study on the effectiveness of virtual lab in E-learning, *International Journal on Computer Science and Engineering,* (2), 2173-2175.

Rodrigues, S. (1997). Fitness for purpose: A glimpse at when, why and how to use information technology in science lessons. *Australian Science Teachers Journal, 43*(2), 38-39.

Stone, D. C. (2007). Teaching chromatography using virtual laboratory exercises. *Journal of Chemical Education, 84*(9), 1488. https://doi.org/10.1021/ed084p1488

Trey, L., & Khan, S. (2008). How science students can learn about unobservable phenomena using computer-based analogies. *Computers & Education, 51*(2), 519-529. https://doi.org/10.1016/j.compedu.2007.05.019

Trindade, J., Fiolhais, C., & Almedia, L. (2002). Science learning in virtual environments: A descriptive study, *British Journal of Educational Technology, 33*(4), 471-488. https://doi.org/10.1111/1467-8535.00283

Tuysuz, C. (2010). The effect of the virtual laboratory on students' achievement and attitude in chemistry. *International Online Journal of Educational Sciences, 2*(1), 37-53.

Ullah, S., Ali, N., & Rahman, S. U. (2016). The effect of procedural guidance on students' skill enhancement in a virtual chemistry laboratory. *Journal of Chemical Education, 93*(12), 2018-2025. https://doi.org/10.1021/acs.jchemed.5b00969

Wartono, W., Batlolona, R. B., Mr Sholikhan, & Huda, C. (2017). Influence of discovery learning-based empirical-theoretical study assisted by Animation PhET on the physics problem-solving in high school. Advances in Social Science, *Education and Humanities Research,* (164), 47-51.

Wieman C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning, *Science,* (322), 682-684. https://doi.org/10.1063/1.2155756

Wieman, C., & Perkins, K. (2005). Transforming physics education. *Physics Today, 58*(11), 36-41. https://doi.org/10.1126/science.1161948

Winkelmann, K., Keeney-Kennicutt, W., Fowler, D., & Macik, M. (2017). Development, implementation, and assessment of general chemistry lab experiments performed in the virtual world of second life. *Journal of Chemical Education, 94*(7), 849-858. https://doi.org/10.1021/acs.jchemed.6b00733

Woodfield, B. F., Andrus, M. B., Andersen, T., Miller, J., Simmons, B., Stanger, R., Waddoups, G. L., Moore, M. S., Swan, R., Allen, R., & Bodily, G. (2005). The virtual ChemLab project: A realistic and sophisticated simulation of organic synthesis and organic qualitative analysis. *Journal of Chemical Education, 82*(11), 1728. https://doi.org/10.1021/ed082p1728