Testing the Efficacy of Virtual Labs in India for Simulation of Optics Experiments at the Undergraduate Level

Laboratory experimentation is an important ingredient of every undergraduate program in science education. The use of virtual and remote laboratories (VRLs) offers several benefits to students, teachers, and instructors. It can mitigate the high costs of procurement of apparatus in traditional labs and can support distance and blended learning. The recent outbreak of Covid-19 has resulted in isolating the students from labs which have made such online laboratories imperative even in the traditional offline education system. They offer a possible alternative to conventional hands-on labs. Such online mode imparts freedom to teachers as well as students to define their experimental goals and objectives. This paper tests the efficacy of the 'Virtual Labs' platform for conducting simulated experiments online in the field of Optics. The learning outcome of the students who employ the same to simulate experiments online is analyzed. The main objective is to explore the limitations posed to the users of such an online lab platform in terms of designing the experiments and visualization of the experiment results and offer suggestions to make such VRLs more efficacious, versatile, and user-friendly.

Keywords: *Science curriculum; Experiments; Virtual Laboratories; Remote Laboratories; Simulations; Optics laboratory*

Introduction

Classrooms are complex, multi-faceted, and demanding places in which to work and successful pedagogies are correspondingly sophisticated. Highly successful pedagogies develop when teachers make outstanding use of knowledge-base for teaching to support high-quality planning and practice. The very best teaching arises when this Knowledge base is supplemented by Educational technology (abbreviated as EdTech) which involves the combination of computer hardware, software, and educational theory and practice to facilitate learning (Robinson et. al., 2008). The use of Web CT, now incorporated into Blackboard Inc., began a revolution of using the Internet to deliver learning (Bates, 2005) making heavy use of web-based training, online distance learning, and online discussion between students (Harasim et. al, 1998). With the optimum use of such technologies, the teaching instructions are designed to address what and how the subject is to be taught to meet the aspirations of learners.

The use of virtual and remote laboratories (VRLs) for undergraduate science courses in a recent phenomenon particularly in developing countries. They have multiple benefits including cost savings in equipment, space, and maintenance staff, a greater possibility of visualization and freedom of design od experiments that would not be possible in a traditional hands-on laboratory, and to carry out a large number of simulations without any restriction (Heradio et al. (2016)). Images or animations used in VRLs provide users with a greater understanding of the system under study. They use the interactive mode that allows users to visualize the response of the system to any external or internal change (Dormido et al. (2005); Sanchez et al. (2002)). Such interactivity features, rich visual contents, and the possibility of an instantaneous visualization of the system response make VRLs a human-friendly tool to learn, helping users to achieve practical experience in engineering control systems. On the other hand, studies conducted on adopting a blended approach to teaching have proved to have a negative effect on students' outcomes (Kozakowski, 2019).

The spread of Covid-19 across the globe coupled with the ensuing lockdown has forced the closure of educational institutions across the nation. This has paved way for distance learning via the online mode. But the tumultuous experiences of teachers and students in remote learning have emphasized a greater need for effective and accessible technology that allows education to scale with learning for all in mind. Although the theoretical classes have readily adjusted to this mode of study using interactive platforms like Microsoft teams and Google Meet, students of science at all levels have faced serious challenges in performing experiments in their practical classes. Mostly, the online mode of conducting practical classes involves the dissemination of theoretical understanding of the experiments in hand without letting the students perform the same. This has led to a situation where the students are bereft of the actual process of performing the experiments and gaining insight into the nuances of the instruments, their adjustment, functioning, and control. Moreover, the theoretical aspects of teaching practical classes don't provide students to visualize the results emanating from the underlying physical processes. This has put severe handicaps in the online mode of education, particularly in sciences.

The above lacunae have generated an inherent demand for an online simulated lab where the students can perform their experiments enumerated in the syllabus. These labs must be immersive, engaging, and necessitate minimal instruction to input the required data. Such ready-to-go online labs with no requirement of plug-ins or additional software like Flash, Java, or other apps permit students to just go straight to the website that gives the sense of performing the actual experiment. This facilitates teachers to deliver their online instructions in real-time. Lincoln (2020) analyzed the efficacy of selected simulated lab websites and proposed steps to make them work better. In India, this has been addressed by the Ministry of Education under the 'National Mission on Education through ICT' where it has come out with a platform 'Virtual Labs (https://www.vlab.co.in)'. The prime objective of the platform is to provide remote access to Labs in various disciplines of Science and Engineering catering to students at the undergraduate level, postgraduate level as well as research scholars. This is aimed to enthuse students to conduct experiments by arousing their curiosity that shall assist in learning basic and advanced concepts through remote experimentation. The above platform aims to integrate lab education by providing a complete Learning Management System around the Virtual Labs where the students can avail themselves of the various tools for learning, including additional web resources, video lectures, animated demonstrations, and self-evaluation.

The salient features of the Virtual Labs encompass assisting the students to perform an experiment by modeling the physical phenomenon by a set of equations and carrying out simulations to yield the result of the particular experiment. This steers the students along a path to provide an approximate version of the 'real-world' experiment. The data thus obtained in the simulation experiment can be compared with the measured data previously obtained by measurements on an actual system. It also can be used as a springboard for students to get the feel of the experiments through the computer interface before it can be actually conducted in the labs in the offline mode. Further, the Virtual Labs are proposed to be made more effective and realistic in coming years by providing additional inputs to the students like accompanying audio and video streaming of an actual lab experiment and equipment.

At the level of pedagogical discourse, these simulations of experiments conform to the constructivist theories (Piaget, 1971) that emphasize the importance of discussion, dialogue, and teachers' ability to scaffold pupils learning beyond their current stage of understanding. The Virtual Labs support a developmental change in the learner and assist the learner to develop a higher level of understanding of the experiments and the underlying physical processes. Thus, it imparts e-learning both in synchronous and asynchronous mode (Kaplan, 2017) It not only offers online real-time interaction of teachers and students but also allows self-paced learning of students and facilitates the online exchange of ideas or information without the dependency of other participants involvement. The Virtual lab is providing an integrated platform where the students are given a theoretical understanding of the physical process involved in the experiments, the detailed procedure with the ability to simulate experiments.

This paper intends to highlight the drawbacks and limitations of the Optics experiments enumerated in the Virtual Lab platform and suggests improvements in such VRLs that can be incorporated in the future to make the platform more effective and versatile. The same suggestions can be incorporated in other subjects and branches as well that have been given space in the said platform.

Limitations of virtual labs

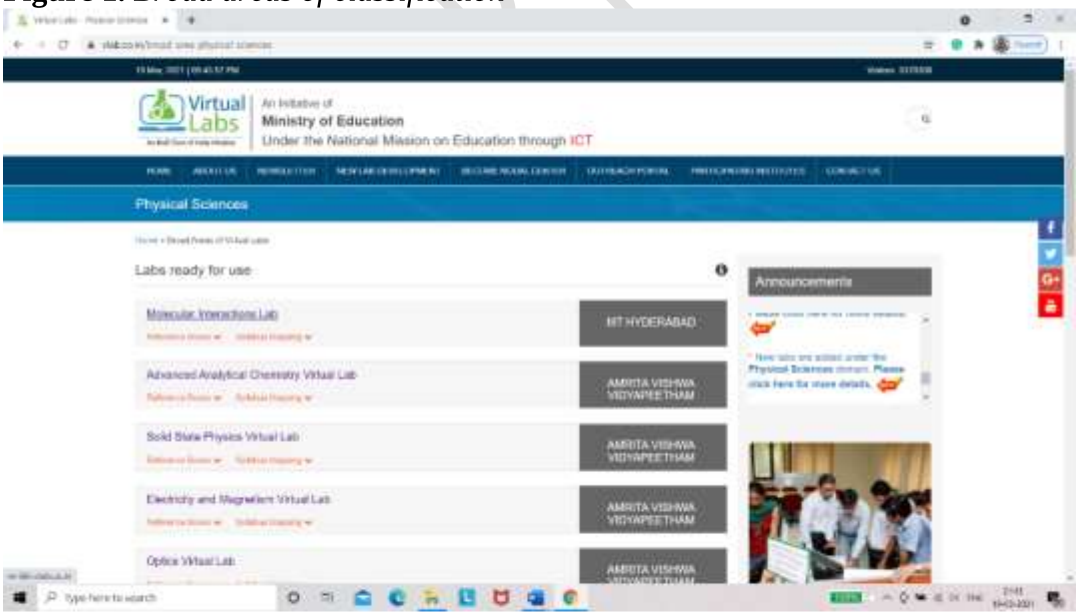
Although the Virtual Lab has proved efficacious, there are inherent limitations that arise in the classification, arrangement, and simulation of experiments enumerated in the platform. The said points are compiled after taking feedback from the students and the teachers who have utilized the same in performing the experiments of the Optics lab as listed in the syllabus of

Delhi University at the undergraduate level. The same can be summarized as follows:

(a) Classification of Experiments

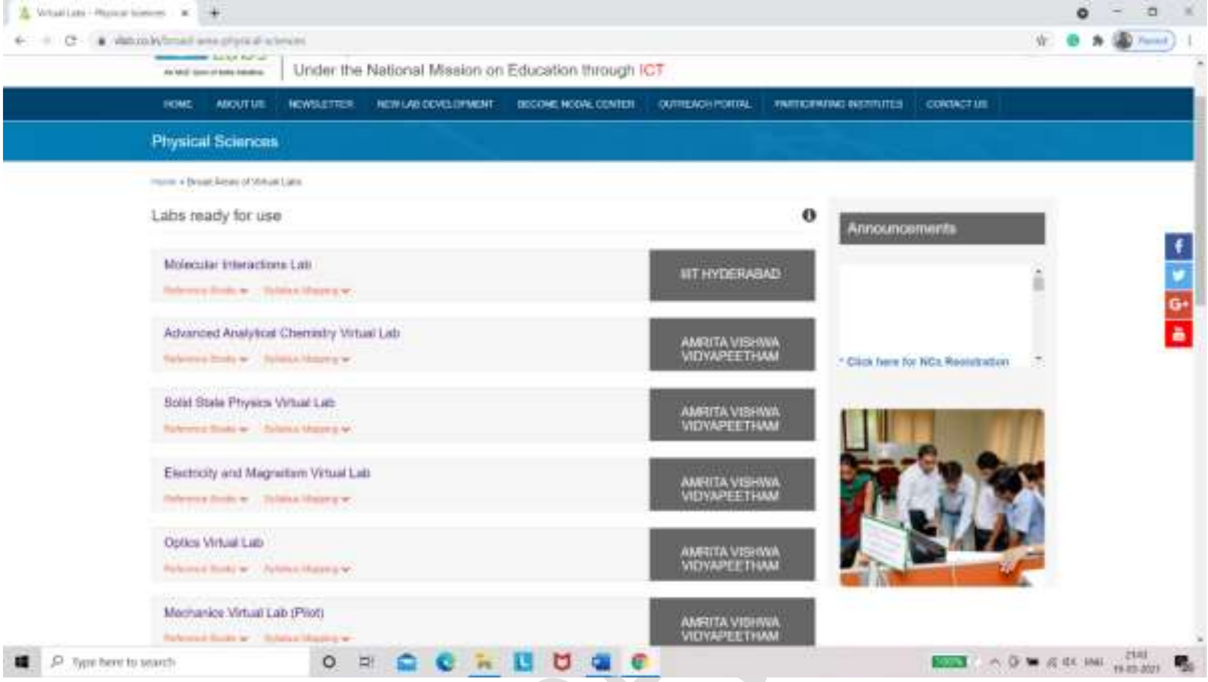
There is an inherent flaw in the classification of experiments in the Virtual Lab platform. When a student logs into the website, it asks students to select the broad field whose experiments have to be performed. After clicking on the desired area of study, say “Physical Sciences”, the page opens where a list of “Ready to use Labs” is arranged according to broad areas of Physics(Figure 1). This encompasses branches of physical science ranging from Molecular Interaction Lab to Virtual Anthropology Labs! This seems strange that Anthropology has been clubbed with Physical Sciences like Physics and Chemistry which is bound to pose problems for its users. The student who wants to learn experiments of Anthropology will least expect the same to be appended with Physics and Chemistry under the head of ‘Physical Sciences’. Anthropology is a global discipline involving humanities, social sciences, and natural sciences. Due to its multi-disciplinary character, it has more resemblance with biology, sociology, and Archeology. Hence this needs to be separated from physical sciences and put separately under the head of Anthropological Sciences.

Figure 1. *Broad areas of classification*



Further, when the students open the said webpage to conduct experimental simulations, say for the Optics lab as enumerated in the syllabus of University Grants Commission/Delhi University, they tend to look for their experiments in the “Optics Virtual Lab” (see Figure 2).

Figure 2. *Labs that are classified under head 'Physical science'*



Most of the experiments listed in their syllabus do not require laser sources. Hence the students will not search for their experiments in the head of "Laser Optics Virtual Lab". But the classification of the experiments based on the source of light used renders the student confused as he/she is not aware of the sources employed in conducting a particular experiment. Moreover, several experiments can be performed using any light source including the mercury lamp, the sodium lamp, or the laser. Hence the least expected head to find "Newton Rings" based experiments would be in the "Laser Optics Virtual Lab". But the Newton rings are placed in the said head which baffles the student and tends to cloud his judgment about the actual aim of the experiment. Although the interference-based experiments can be performed by any monochromatic light source including Laser, the said experiment should ideally have been placed in the head of "Optics Virtual Lab" rather than the "Laser Optics Virtual Lab". These avoidable distortions in the classification of experiments should be done away with to make the platform user-friendly and scientific.

(b) No description of Instruments and it's set up

Figure 3. *Experiments listed under the head of Optics*

When the student clicks the head, say "Optics Virtual Lab", several experiments are listed (Figure 3). Most of them are those are required to be conducted in any undergraduate course of physical sciences. But the website does not mention anything about the nuances of the construction and functioning of the spectrometer or the intricacies of setting it up before the experiment. A spectrometer is a device for measuring wavelengths of light over a wide range of the electromagnetic spectrum that is used in most optics experiments. Although the procedure details the instructions given anywhere on the website about the procedure to set up the spectrometer before it is used to measure the angles and the wavelengths in a given experiment, it is not enough as the students need detailed knowledge of the same for better understanding and efficient conduct of the experiments in online mode. The same is true for other instruments like traveling microscopes and optical devices like prism and plane transmission grating.

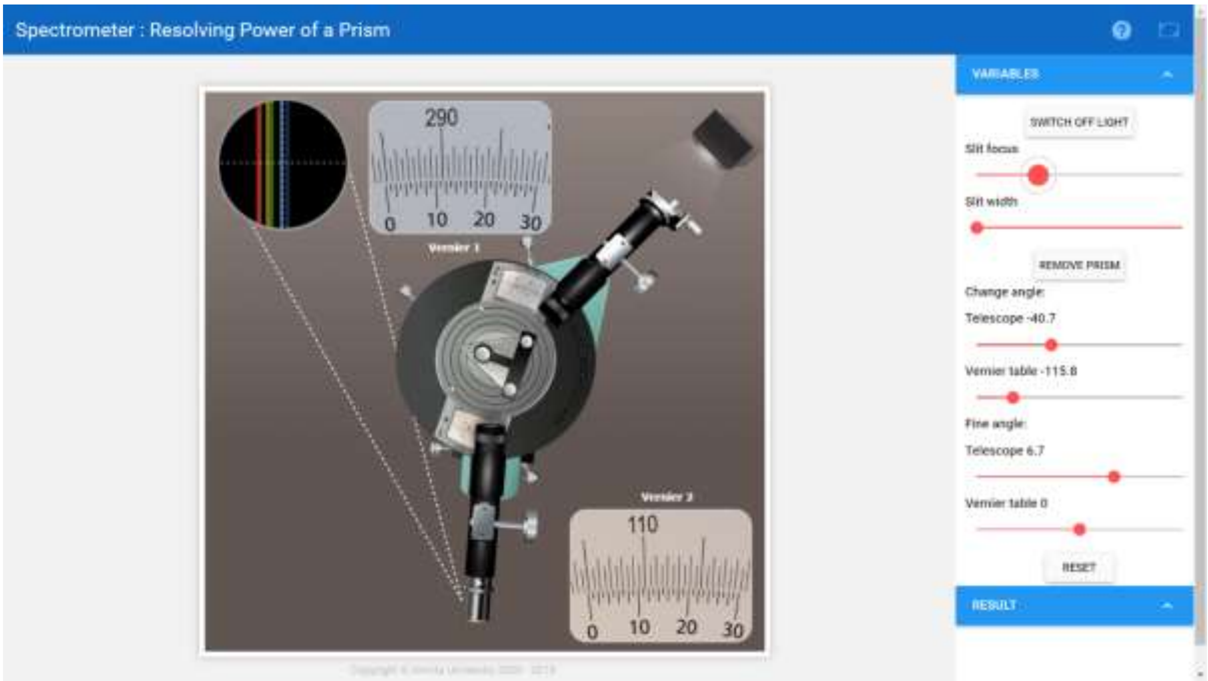
(c) Inadequate Simulation process

Although the website is commendable in its aim to prove students with an integrated platform to conduct a simulation of experiments, there are glaring inadequacies in the simulation process that limits the efficacy of the platform. These inadequacies are encountered by the students who had availed the benefits of the said website. Some of them that were experienced while simulating the Optics experiments are recorded as follows:

i. Source of light

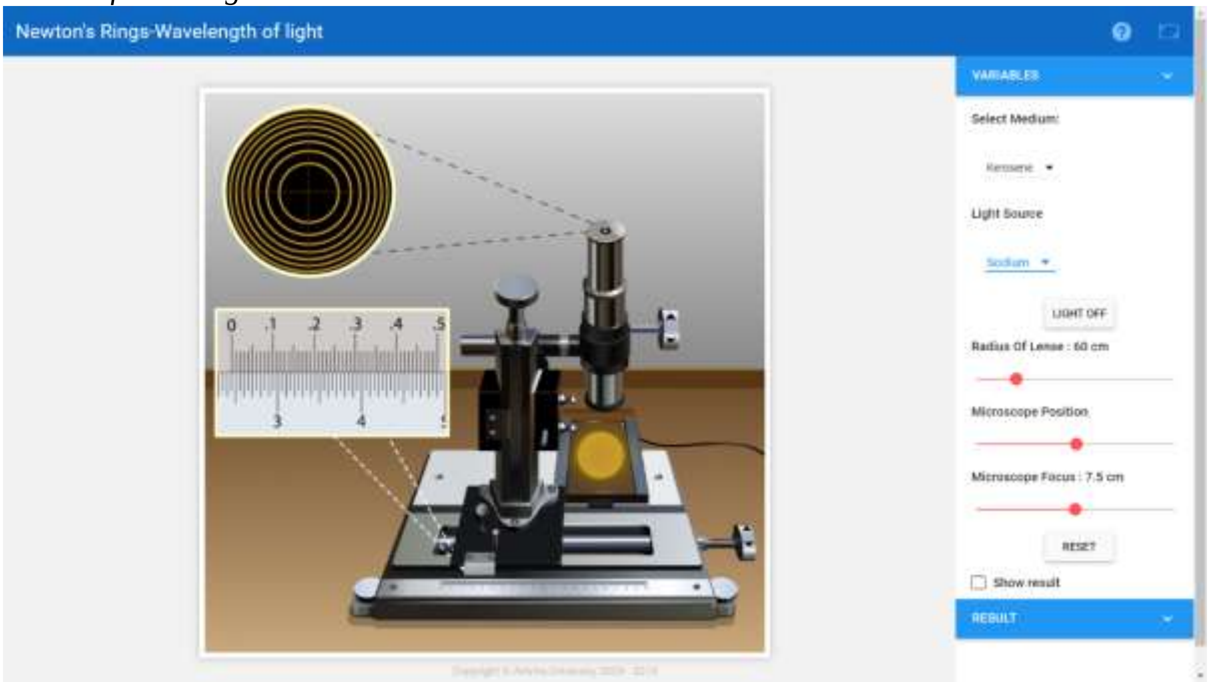
There are several experiments in Optics that can be conducted using either the white mercury lamp or the monochromatic sources like Sodium lamp or the laser light. Moreover, the resultant physical mechanism that can be viewed using such categories of light sources indeed assists the students in visualization and interpretation of their optical effects and help them understand the physical process.

Figure 4. *Simulator of the 'Resolving power of the prism' experiment in Virtual Lab*



For example, if one simulates the experiment to calculate the resolving power of the prism as shown in Figure 4, the same is done using white light from the mercury lamp. However, there is no option in the simulation process (Figure 4) to interchange the source of light, say, with a monochromatic sodium lamp which comprises wavelength doublet of 5890 A and 5896 A. If there was an option inbuilt in the simulation process, the inability of the prism to resolve the D-lines of the sodium spectra can assist the instructor to explain the limitations of the prism in terms of its resolving power. Similarly, the optics experiments such as Newton rings and Diffraction Grating simulated with help of monochromatic light sources like Sodium light and laser can offer deep insight to the students in terms of their attributes of resolving power and dispersive power. It is worthwhile to add here that the experiments enumerated under the head of 'Laser Optics Lab' have a versatile algorithm that offers greater choice to students in the matter of choosing the source of light used and the medium in which the interference pattern is formed (Figure 5). But it still lacks the option to use Lasers as a source of light to simulate the same.

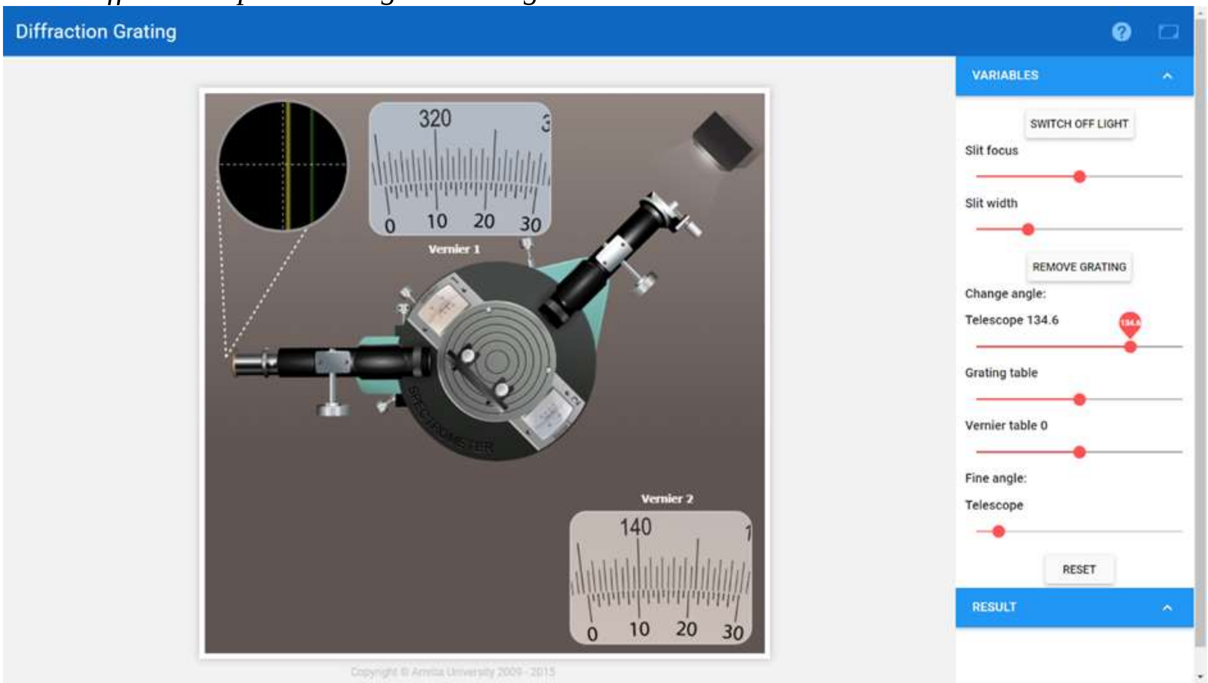
Figure 5. *Simulator of the 'Newton Rings' experiment in Virtual Lab. The choice of selecting medium and sources are evident*



ii. Quality of instruments/apparatus

The simulation of the experiments in the Virtual Labs has an inherent limitation of using the instruments and apparatus of fixed Least counts and quality. For example, the typical analytical Student transmission diffraction Grating contains 15000 LPI which can form first and second-order diffraction patterns with sodium light (Figure 6). Using such gratings, the sodium D lines are easily viewed in the lab. However, if the diffraction gratings of 600, 1200,2500,7500 and 15000 lines per mm were given as an option in the simulation process of the said experiment, the students could have understood the interdependence between the number of orders of spectra visible with a given grating and the grating spacing, allowing him to deduce that more spectra were visible with coarser gratings. This is not readily possible in a traditional hands-on laboratory, which adds to the effectiveness of the virtual labs in online mode. Similarly, if the student wants to study the factors on which the dispersive power of a prism depends, there is no choice in the simulation algorithm to select a prism of different materials.

Figure 6. *Diffraction Grating' experiment in Virtual Lab showing second-order diffraction spectra using sodium light*



The Refractive Index of flint Glass (μ=1.65) is relatively higher than that of crown Glass (μ=1.51) which maximizes the dispersive power of flint glass prism. But the same cannot be inferred while performing the simulation of an experiment to find the dispersive power of a prism.

Finally, if the simulation had the option of selecting the Least count of the measuring instruments like the spectrometer and the traveling microscope, it would have made a difference, particularly while measuring closer wavelengths like the sodium doublets. They would have allowed students to attain more accuracy in experiments such as measuring the resolving power and dispersion power of prism and diffraction grating.

Learning outcomes of students

The introduction of virtual and remote laboratories during the pandemic times has opened floodgates to access the change in the learning objectives and the ensuing outcomes from the said blended learning process. After analyzing the academic progress of 60 students of Physics at the undergraduate level, the following observations are in order:

a) About 31 students had a tough time adjusting to the blended mode of learning. This was due to the mismatch of the online platform with the cultural expectations of the users, who are more inclined to the physical form of instruction at the classroom level with original instruments and physical laboratories. It was inconvenient for them to grasp the simulation process. Some of them showed mental blocks towards using the same and offered resistance to the technology which delayed the grasp of the said learners on the experiments at hand. The consequence of cultural friction in the deliverance of education is quite evident which has a negative impact on the learning outcomes of the students. The delaying effects resulting due to the cultural backgrounds of the learners corroborate the findings established in several studies (Callahan 2005a; Callahan 2005b; Hargittai & Shafer 2006).

b) After the transitional period of adjustment was over, 45 of the total students were seen to perform the experiments enumerated in the syllabi with relative ease. They could grasp the rudimentary aspects of the experimental observations and be able to calculate the least count of the instruments and use the same to obtain the final results. However, the simulation process also resulted in undue weightage given by the learners on the final results of the experiments while bypassing the intricacies of adjustments of apparatus in hand to reduce the errors in the final results they obtained. The measurement of physical data during the simulation process trivialized the concept of accuracy and the level of uncertainty in measurements. The simulation process minimized the gross errors resulting from human oversight and other mistakes while reading and recording observations. The most common errors, the human error in the measurement fall under this category of measurement errors. Thus, the repeating of experiments by increasing the number of readings to reduce errors in the measurements had no meaning in the online process. Since the inbuilt algorithm of the VRL's offers no flexibility in the design of the apparatus used, the Instrumental Errors that arise due to faulty construction and calibration of the measuring instruments were not appreciated by the users. Consequently, the effect of wear and tear of instruments, misuse or neglect of the same which changes the reading of the equipment and results in most common of the errors like the zero error did not find appreciation during the learning process. The same was also true for the Random errors that arise due to random and unpredictable fluctuations in experimental conditions when the experiments are performed under laboratory conditions. Few errors like the Observational Errors that arise due to an individual's bias, lack of proper setting of the apparatus, or an individual's carelessness in taking observations did manifest itself during the simulation process, but their role in the final outcome achieved by the users was minimal due to exactness of the readings offered on such platforms.

c) The mature phase of performing the experiments was visible in almost all the students who adapted to the new technology. Although the instructions imparted encouraged students to design their experiments and compare the results, they were handicapped by the limitations offered in the simulation process as enumerated in the study. Most of the students did establish results particularly related to resolving and dispersive power of the prism and diffraction grating vide employing other methods. But they could not perform the same experiments in optics using different light sources or with an instrument with a better least count which posed a limitation on the designing of experiments to achieve a specific outcome. This establishes that with a versatile simulation process incorporated in the VRL's, its efficacy can be augmented in form of greater flexibility in design and performing the experiments.

(d) In all, 31 students were able to complete all the experiments enumerated in the syllabus. Only 13 students were unable to perform less than half of the online experiments satisfactorily. The rest were short of few experiments. This again reflects the resistance to the technology and the adaptability of the students in grasping the reality of the situation and performing the same online in the blended mode without the use of actual experiments. In terms of showing excellence in the same, only 14 students showed the spark of adding versatility in their approach. This points to a moderate level of satisfaction of the students with an online learning environment with which they interacted if the same is measured in terms of the learner's academic outcome.

Suggestions offered

(a) Classification of experiments based on physical processes.

As discussed in the last section, the classification of the experiments based on the source of light used in rather unscientific and flummoxes the students about the aim of the experiment in hand. It would be advisable to categorize the same on basis of physical processes like interference, diffraction, polarization, dispersion, and total internal reflection, to name a few. This will impart clarity to the students on the underlying physical processes involved in an experiment and make the Virtual Labs more scientific and user-friendly. Further, it will go a long way in allowing students to adopt the same and reduce their inhibition in espousing the blended approach. Any confusion at the entry-level augments the resistance that the students offer to their adaptability to new technology.

(b) Introduction about the apparatus and instruments used during the simulation process

At the start of the simulation process, there should be a video tutorial on every aspect of construction and working of the instruments used in the experiments. These are mostly common instruments like spectrometer, traveling microscope, Polarimeter, Michaelson interferometer, etc. The video should explain the construction of the instruments, the set-up process, and measurement of a physical quantity like angular deviation and wavelength using them. The same can be transcended to other branches like mechanics, electronics, Modern Physics where similar videos can be uploaded for the students to educate them with the working of instruments such as compound pendulums, Carey foster bridges, Searle’s apparatus, Melde’s experiments, Maxwell needles, CROs, function generator, discharge tubes, Hall effect, etc.

At the same time, it is advisable particularly in the optics lab to educate the students about the optical components like a prism, plane transmission grating, Newton Rings setup, quarter and half-wave plates, Nicol prisms, etc. This will enhance the capability of students to use the same and bring clarity regarding the underlying physical processes involved in the experiments. Moreover, it shall make ‘Virtual Lab’ an integrated platform for the students to conduct experiments in virtual mode.

(c) Option to use multiple sources of light

The option to choose light sources in the simulation algorithm imparts the students the freedom to design their experiments and enhance their cognitive abilities and critical thinking. Several experiments can be performed using white light as well as monochromatic sources like sodium and laser. This will allow the students to simulate experiments using various sources and visualize the change incurred due to the same. This shall facilitate higher-order learning using the virtual labs. Using a simulated practical activity, students can structure their learning outcomes and improve engagement and knowledge retention. When studying a particular topic, a practical simulation of experiments in the virtual laboratory can felicitate an open-ended exercise mechanism where students are encouraged to test their hypotheses and draw conclusions from the same.

(d) Option to decide the least count of instruments used and quality of apparatus

The smallest value that can be measured in an instrument is called the Least Count of the Instrument. The least count defines the main part of a measurement and occurs in both random as well as systematic errors. The least Count Error depends on the resolution of the instrument. The Least Count Error can be calculated if we know the observations and least count of instruments. High-precision instruments are employed to improve experiment techniques, thereby reducing the least count error. To reduce the least count error, the arithmetic mean of all the observations is taken to make the mean value closer to the actual value of the measurement. In Optics experiments, a small change in the Least count of the instruments used can vary the final result significantly. The students must be aware of the Least count errors and how it affects the outcome of their observations. To facilitate it, the simulation algorithm must extend the choice to students to choose the instruments with the Least count which are commercially available in the market. For example, spectrometers generally come in a Least count of 1min or 20 seconds. Students can use the spectrometer of better Least count while performing experiments such as the Resolving power of grating where they need to measure two close wavelengths. The same is true for traveling microscopes used in Newton Ring experiments. This shall enable the students to design their experiments with an additional objective of reducing the random as well as systematic errors occurring in an experiment.

(e) Use of multimedia to explain the simulation process

Audio-visual material can provide useful aids for learning when integrated into computer-based teaching systems. Multimedia coupled with other educational software support effective and quality instruction. Woolfe and Hall (1995) demonstrated that truly interactive systems can evolve into multimedia pedagogues that can alter ways of teaching and learning. An effective multimedia interface allows the integration of several media forms to disseminate knowledge regarding a particular topic. Several media presentations such as text, process descriptions. about a single topic can be combined and offered to students before they attempt a hands-on simulation of experiments. These may include a video presentation on the procedure to conduct the said simulation and note down observations. Small video presentations about the introduction of instruments employed in an experiment and optical devices shall impart clarity in the mind of users and make the platform effective and user-friendly. Hence, the students will gradually construct their understandings of scientific ideas and develop thinking processes that scientists use. (Thompson and Zeuli, 1999)

(f) Steps to alter the algorithm to allow appreciation of errors during the experimental process

The Designers of resources such as online learning environments in form of VRL's must be done to appraise the users of the several types of errors that they shall encounter during the hands-on conduct of same with actual instruments and apparatus in the laboratory. Developers of software for online learning environments could identify aspects of the environments that can be inserted in the VRL's to draw the attention of the users regarding the identification of such errors. Such aspects of conducting the experiments should be made adequately flexible by altering the environmental factors or inserting the option of providing systematic errors in the instruments in the virtual simulation designs.

Conclusions

The technologically driven world has made complex problem solving and critical thinking the basic ingredient in any pedagogical method. The same can be achieved by helping students to draw links between observations and ideas, particularly in the field of experimental sciences. Software developers of such an online environment should incorporate the suggestions enumerated in the present study to allow compensation for various limitations posed by such platforms and mitigate them. Instructional designers may use these findings to identify the aspects of online learning environments that require adjustment or special treatment to address the cultural expectations and needs of their target learners. The current practices employed in labs do not support developing students' understanding of scientific concepts and explanations adequately. This requires structuring pedagogical methods by incorporating multimedia resources like simulation. This encourages students to develop self-reliance and design experiments themselves on VRLs rather than achieving a predetermined outcome in a hands-on Laboratory. This enhances their skills in problem-solving and critical thinking to achieve higher-order skills of logical sequencing. Further, this shall improve the count of students to adopt science as their profession either on academic or technical routes by imparting practical skills and attitudes that will be an asset in their future careers. The acquirement of transferrable skills in the youth bodes well especially for developing nations that are focused on creating a skilled-based society to mitigate poverty and unemployment.

The 'Virtual Lab' platform has announced the advent of an effective VRL platform for science and engineering students in India that shall also felicitate remote and online education in the country. This mitigates the issues of suitable space, time, and resources. Hence it is in the interest of the entire nation that such VRLs be made more effective, versatile, and user-friendly to popularize them as an alternative to hands-on laboratories. The suggestions presented in this paper shall go a long way to promote a constructivist view of inquiry-based learning for undergraduate students using the 'Virtual Lab'. Further, it can also serve as a guideline for the other VRLs that aim to promote virtual experimental learning for undergraduate students.

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