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ORIGINAL RESEARCH

An Analysis of Health Science Students' Preparedness and Perception of Interactive Virtual Laboratory Simulation

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Abstract

The achievement of learning goals via laboratory practical depends on both extrinsic and intrinsic factors. They could be limited by laboratory time, incurred cost, safety, self-efficacy, inadequate prior preparation by learners, and different learning styles. Hence, virtual laboratory simulation (vLAB) may be an appropriate e-learning tool to overcome these restrictions. In this study, student's perception of the usefulness of vLAB was determined by using deoxyribonucleic acid (DNA) gel electrophoresis and polymerase chain reaction (PCR) as case examples. The perception of Year 2 and 3 health science undergraduate students' ($N=87$) was studied using a questionnaire consisting of 12 items, rated on a 5-point Likert-scale. The attainment of learning outcomes was assessed using pre-and post-tests containing multiple-choice questions (MCQs). In addition, student's experience and learning from the vLAB were further explored using qualitative analysis. Although there was no significant difference between the mean scores of the pre-and post-tests, results showed that all participants perceived vLAB well, with a median score of 4 (Agree) for all items in the questionnaire. It provides a meaningful learning experience and an authentic environment where students feel safe to practice what they have learnt in lectures. Moreover, vLAB facilitates individualised learning and enhances self-efficacy among students. In conclusion, vLAB prepares students for physical laboratory sessions by activating the prehension dimension of Kolb's learning cycle, therefore complementing and strengthening the attainments of health sciences laboratory learning goals and outcomes.

Keywords Constructivism · Experiential learning · Individualised learning · Virtual laboratory simulation

Introduction

By nature, scientific discoveries are inquiry-based activities as they incorporate real-world learning where learners construct their knowledge. Laboratory practical is essential to help health science students to develop key psychomotor skills, understand the process of scientific study, and comprehend scientific concepts through inquiry and experiential learning [1, 2]. Students can acquire psychomotor skills (practical skills), collaborative working skills, and a sense of awareness of personal and environmental safety through experiences gained during the laboratory practical sessions [1]. As a result, students can apply scientific concepts and assimilate these practices into their daily lives [2]. However, laboratory practical can also be a time-consuming, resource-intensive process, and the impact varies depending on learners [3].

Interactive virtual laboratory simulations (vLAB) are tools derived from technological advancement to enable individualised and active learning of science [4, 5]. The combination of vLAB and hands-on exercises in the physical laboratory may strengthen learning outcomes. It also impacts students' ability to make accurate explanations and reasonable predictions of the experimental phenomena [6]. Virtual lab simulation is frequently classified as constructivist learning environments, where students can participate in the learning

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process actively and construct newly acquired information [7, 8]. The constructivist theory of learning strongly suggests that learning with understanding is enhanced when learners can use their prior knowledge and experience to construct and contextualise new understanding [9]. However, more evidence is needed to determine whether the vLAB is aligned or designed based on constructivist theory.

Like many other learning tools, vLAB has its limitations. One of them is the lack of opportunities for collaboration and interaction between students and teachers as they are asynchronous in nature [10]. Students also have less opportunity for troubleshooting as vLAB does not progress if students make mistakes [11]. Other technical aspects such as interaction design, visualisation, and pedagogy also play major roles in determining the achievement of learning outcomes [12]. Besides, students may not be able to master the real psychomotor (practical) skills as they are not exposed to the real devices in vLAB [13]. For institutions, the shift towards vLAB can be laborious and costly whether it is developed in-house or subscribed. Therefore, careful consideration for effective and sustainable implementation is needed.

The long-term benefits and limitations of using virtual learning either as a stand-alone or complementary learning tool need elucidation to inform both decision making and investment into these resources. As the vLAB is relatively new and not easily accessible, student's acceptance needs further investigation. Furthermore, accreditation bodies that emphasise graduate competencies and quality will also need evidence of careful evaluation of vLAB. This study was undertaken to gain insight into biomedical and medical biotechnology students' perception of the usefulness of vLAB and the effect of vLAB on students' learning. This is more so as limited data is available for these health science disciplines. During this COVID-19 pandemic, graduates of these disciplines are highly sought by both diagnostic and research laboratories to reduce the testing backlog, developing diagnostic kits, and vaccines [14]. In view of this, it is crucial to equip students with a strong conceptual understanding of laboratory techniques. In addition, this study used both qualitative and quantitative approaches, enabling students' perception about vLAB to be explored in depth to verify and broaden the quantitative findings.

Table 2 Gender of participants of the respective cohort and programmes participated in the qualitative study

Programme	Cohort	Semester	Gender	
			Male	Female
Biomedical science	BM118	5	1	3
	BM119	3	1	6
Medical biotechnology	MB118	5	7	1
	MB119	3	3	1

Methods

Study Setting and Participants

This study was conducted among Year 2 (semester 3) and Year 3 (semester 5) students in the Bachelor of Science (Hons) in Biomedical Sciences (BM) and Bachelor of Science (Hons) in Medical Biotechnology (MB) programmes, at the International Medical University (IMU). Both BM and MB programmes in IMU are 3-year (six semesters) programmes. Both curricula are outcomes-based, aiming at producing graduates who are knowledgeable, competent, ethical, and professional.

A total of 87 students (53 females, 34 males) aged between 20 and 24 participated in the quantitative study. Their perception about the vLAB on DNA gel electrophoresis and PCR was evaluated using a questionnaire. Eight of the participants were international students, and the others were local students (Tables 1 and 2). From these participants, 23 participated in the online individual interviews on a first come first served basis to further explore their personal views and perspectives about vLAB. All of them were Malaysian students with an age range between 20 and 23.

Selected Virtual Laboratory Simulation

The scope of PCR and DNA gel electrophoresis are covered in the semester 3 modules of both programmes. The applications of both laboratory techniques are revisited in Semester 5 of both programmes.

Table 1 Number of students of the respective cohort and programmes participated in the quantitative and qualitative studies and its percentage of the targeted population

Programme	Semester	Quantitative ($N=87$) (% of population)	Qualitative ($N=23$) (% of population)
Biomedical sciences	5	35 (64.8%)	4 (7.4%)
	3	32 (54.2%)	7 (11.9%)
Medical biotechnology	5	15 (100.0%)	8 (53.3%)
	3	5 (100.0%)	4 (80.0%)

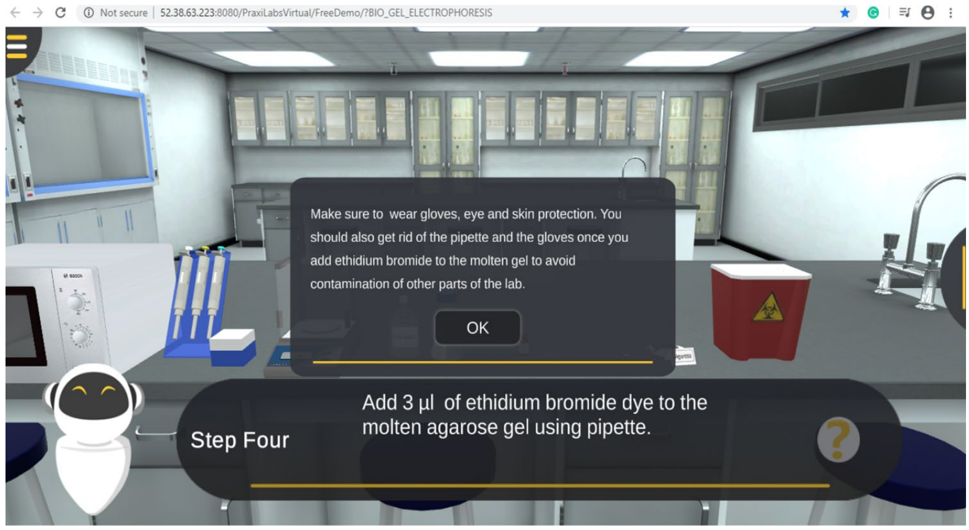

Fig. 1 The gel electrophoresis virtual laboratory available at (http://52.38.63.223:8080/PraxiLabsVirtual/FreeDemo/?BIO_GEL_ELECTROPHORESIS)

vLAB from Praxilabs was selected for its ability to simulate the process of DNA gel electrophoresis most closely compared to the physical laboratory set up as determined by content experts (http://52.38.63.223:8080/PraxiLabsVirtual/FreeDemo/?BIO_GEL_ELECTROPHORESIS) (Fig. 1). In this virtual laboratory, students had to complete the tasks of agarose gel preparation, sample loading, electrophoresis, and view the DNA samples. For the PCR, students had to complete the tasks of mixing of PCR reagents and complete the PCR reaction https://learn.genetics.utah.edu/content/labs/pcr/ (Fig. 2). Both the selected vLAB are free and open-source programmes, and students could access them anytime and anywhere. The hands-on activities were simulated step by step hence providing a session similar to an actual experiment. This allowed students to visualise the laboratory procedures and interact with the program actively. The duration of each program is approximately 5–15 min.

Study Design

Prior to the conduct of this study, all students had gone through lectures on both PCR and DNA gel electrophoresis. Unlike Year 2 students, Year 3 students had the opportunity to experience the physical laboratory practical on both PCR

Fig. 2 The PCR virtual laboratory simulation available at https://learn.genetics.utah.edu/content/labs/pcr/

and DNA gel electrophoresis before experiencing the recommended vLAB. The perceptions of students about vLAB were first determined quantitatively using a questionnaire. The attainment of learning outcomes was assessed by evaluating the students' performance using pre-and post-tests of MCQ. The effect of vLAB on student attitudes was further explored using qualitative interviews. The interviews were ceased when data saturation was accomplished.

Quantitative Study

The students were given approximately 1 week to access the vLAB programmes. After the vLAB activities, the participants' perception of vLAB was collected using a questionnaire with 12 items (Appendix). This questionnaire was piloted by a small number of semester 6 students from MB to check validity. The students affirmed the questions were clear and relevant. Each item is rated on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree) with total scores ranging from 14 to 60. All data were collected using Google Forms. The internal consistency reliability of the questionnaire (Cronbach's alpha) was determined using the SPSS version 26 (IBM Corp. Amonk, NY). The median score analysis was conducted, and data of year 2 and year 3 students were compared.

The impact of virtual lab sessions on the attainment of learning outcomes among the participants was assessed through student's performance evaluation before and after the vLAB activity on PCR. The test consisted of 10 MCQs which were blueprinted to the learning outcomes related to the experimental concepts of PCR. The questions in both pre-and post-tests were different to prevent students from memorising the answers from the earlier tests, with similar difficulty and complexity. It is important to note that the content and face validity of the questions were confirmed by subject matter experts. The test reliability and item metrics were also determined. The normality of the data and the mean scores were analysed using SPSS version 26.

Qualitative Study

The effect of vLAB on student attitudes was studied using qualitative analysis. Information that corroborates the scores obtained from the quantitative survey and additional details on students' learning with vLAB were obtained from individual interviews with 12 Year 3 students and 11 Year 2 students from both BM and MB programmes. The participants were asked about their perceptions of vLAB before and after experiencing the vLAB activities. The interviews were conducted based on an interview guide comprising a set of pre-determined open-ended questions that were developed based on Kolb's learning cycle to ensure the interview process was similar between all interviews [15].

The explorative questions covered in the semi-structured interview were as follows:

1. How does virtual lab help you to visualise the practical procedures in the laboratory?
2. What do you like about virtual labs?
3. What do you dislike about virtual labs?
4. How is virtual lab different from a live demonstration by a lecturer before the hands-on experiment?
5. What is the information/knowledge you obtained from virtual labs that you could not obtain from a conventional lab practical session?
6. Any suggestions for improvement?

Each interview took approximately 30–45 min and was conducted in English (the language of teaching) with explorative open-ended follow up questions. All interviews were conducted using the Microsoft TEAMS meeting platform, audio-recorded, and manually transcribed verbatim. The interviews were stopped when data saturation was reached when no new theme emerged from the interviews, indicating all the major themes have been identified.

Thematic analysis [16] was carried out to analyse and identify the themes related to the perceptions of students about vLAB and its contribution to the contextual understanding of laboratory techniques. The researchers of this study are from various disciplines, where one teaches in both health science programmes, while two others teach in the pharmacy, medical, and dentistry programmes. In addition, two of the researchers are trained in education sciences. The interview transcripts were studied repeatedly by two of the researchers (KYY and HME) to become well versed in the contents. The interviews were then coded independently, and the emerging themes were identified. The identified themes were discussed among the researcher team members and checked with the original transcripts to ensure they were grounded in the data. Regular meetings were held between researchers to obtain agreement on the recurring themes. Towards the final stage of the study, no new themes emerged, indicating all the major themes have been covered.

Results

Quantitative Study on Student's Perception of vLAB

Students' perception of vLAB is shown in Table 3. The internal consistency (Cronbach's alpha) of the items for Year 2 and Year 3 were 0.849 and 0.806 respectively, demonstrating acceptable reliability of the questionnaires. From the statistical analysis, the median score of all items were 4 (Agree) for both Year 2 and Year 3 students. They agreed that vLAB was easy to use; learning objectives were clearly defined, felt confident in using and navigating around the platform; the activities were engaging and able to help them to visualise the concepts of laboratory techniques which guided them through the experimental procedures. Moreover, the students agreed that vLAB stimulated their interest to search for additional information, stimulated them to recall their prior knowledge, and helped them to retain their knowledge of the laboratory techniques. They also felt safe to make mistakes and agreed that making mistakes in vLAB helped them to learn the experimental procedure. In addition, the students also agreed feedback was provided to them when they made mistakes in vLAB. On the other hand, the reliability of the tests on the attainment of learning outcomes was determined using the KR-20 values, which were 0.4604 and 0.4710 respectively for the pre-and post-tests, while mean scores of pre-and post-tests of the PCR component were 6.64 and 6.47 respectively ($p > 0.05$).

Thematic Analysis of Interviews

The students' interviews were subjected to thematic analysis, and three themes were identified: educational values, individualisation of learning, and areas of enhancement. The emergent themes and sub-themes based on the interviews are shown in Table 4.

Table 4 Emergent themes based on interviews

Themes	Sub-themes	Total no. of quotes
Educational values	Experiential learning	117
	Instructional design	161
	Learning environment	15
Individualisation of learning	Individualised learning to personal needs	26
Areas of enhancement	User experience	36
	Feedback	16
	Collaborative learning	12

Educational Values

Experiential Learning

All participants appreciated the true-to-life laboratory experience gained from vLAB. They also agreed that vLAB gave them a better understanding of the practical procedures and it served as a good platform to prepare them before carrying out the physical experiment.

> vLAB is more to prepare you beforehand. But in terms of knowledge, I just feel like it helps to strengthen your conceptual knowledge... And to give you a brief overview before you do a real-life experiment. (Participant (P)8)

Table 3 Students' perception of vLAB

Perception statements	Year 2 ($N = 37$) Median ± SEM (IQR)	Year 3 ($N = 50$) Median ± SEM (IQR)
The interactive virtual laboratory simulation was easy to use	4.00 ± 0.119 (1)	4.00 ± 0.136 (1)
The learning objectives were clearly defined at the beginning of the interactive virtual laboratory simulation	4.00 ± 0.075 (0)	4.00 ± 0.09 (0)
I felt confident in using and navigating around the interactive virtual laboratory simulation programme	4.00 ± 0.132 (1)	4.00 ± 0.112 (1)
I found the activities in the interactive virtual laboratory simulation were engaging	4.00 ± 0.126 (1)	4.00 ± 0.105 (1)
Interactive virtual laboratory simulation helped me to visualize the concepts of PCR and DNA gel electrophoresis	4.00 ± 0.102 (0)	4.00 ± 0.084 (1)
Interactive virtual laboratory simulation guided me through the steps in the experimental procedure	4.00 ± 0.109 (0.5)	4.00 ± 0.109 (1)
Interactive virtual laboratory simulation stimulated my interest to search for additional information	4.00 ± 0.123 (1)	4.00 ± 0.118 (1)
Interactive virtual laboratory simulation stimulated me to recall my prior knowledge about PCR and DNA gel electrophoresis	4.00 ± 0.096 (0.5)	4.00 ± 0.086 (1)
The interactive virtual laboratory simulation helped me to retain my knowledge of PCR and DNA gel electrophoresis	4.00 ± 0.103 (0)	4.00 ± 0.077 (0.25)
I felt safe to make mistakes in the interactive virtual laboratory simulation as I could repeat as many times as I liked	4.00 ± 0.109 (1)	4.00 ± 0.100 (1)
Making mistakes in the interactive virtual laboratory simulation helped me to learn the experimental procedure	4.00 ± 0.116 (0.5)	4.00 ± 0.107 (0)
The interactive virtual laboratory simulation provided feedback to me when I made mistakes	4.00 ± 0.136 (1)	4.00 ± 0.157 (1)

*1 = completely disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree

SEM standard error of the mean

> I feel like we get a chance to go through the whole process and can be more understand the process from the beginning to the end and we also get the chance to play around with the instrument, reagents and apparatus using our mouse. I think that's quite interesting, quite fun. (P11)

vLAB helped the students minimise mistakes and reduce unnecessary waste of laboratory resources during the actual experiments.

> Before a real-life practical, so to minimize your mistakes, to enhance your understanding first, this can in turn waste fewer resources. (P19)

In addition, laboratory safety issues could be incorporated in vLAB. The students were familiarised with the health and safety aspects of the experiment, hence should remember to exercise safety precautions during the physical laboratory sessions.

> This vLAB is also very detailed like it will guide me step by step to perform the experiment, and also sometimes uh it will remind me the safety precaution like wearing glove, discard the pipette tip and also do not reuse the pipette tip. (P22)

The senior students could use vLAB as a resource for revising the laboratory procedures after carrying out the experiment.

> It was a great tool for revision, like a refreshing of your memory from your previous experiences. (P12)

Some participants felt more confident in conducting the experiment with less guidance from the laboratory demonstrators after going through vLAB. However, assistance in operating the instruments was still required.

> I think the vLAB is good to prepare me before I go into the actual practical... So, once I walk in, I'm prepared enough to just carry out the experiment on my own. (P2)

Students also commented vLAB is interactive, and they enjoyed doing the practical virtually more than watching the pre-recorded video demonstrations of the laboratory techniques, which substituted the live demonstration in the physical laboratory when online learning was introduced during the COVID-19 pandemic.

> It will be more interactive and more fun. 'cause ... it's quite fun doing the practical, I mean the vLAB, than just watching videos of people doing it'. (P14)

However, students were concerned that they were not able to gain psychomotor skills from vLAB, such as pipetting techniques and handling of equipment.

> There's a lot of these techniques. You can only learn in real lab, but you can't learn in vLAB, and the technique involved. (P10)

Instructional Design

All students acknowledged that they are guided through the steps in vLAB with clear instructions and explanations. These have helped them to visualise the procedures in the physical laboratory.

> I'm a very visual person like whenever I learn something, anything I need to visualise it to remember. So when I'm able to get animation and follow the flow it makes my mind easier to remember rather than, like reading the manual and just words. (P7)

Furthermore, the principles behind the procedures are clearly explained using close to real animation in vLAB; hence, it can act as a bridge between theory and real-life events, thus enhancing their conceptual understanding and stimulated them to recall the knowledge that they have learned in the past.

> In vLAB, I feel like one thing is it can compact a lot of knowledge in a very short time through the use of animations and videos. (P4)
> It helped me get better understanding on the procedures itself and also … extra like information about it, so it's much more clear when doing the vLAB. It's like you're doing the lab itself. (P21)
> Help me to revise, recall all those things, which I have learned but then I forgot. (P23)

In comparison to the live demonstration by the faculty before hands-on sessions, students felt vLAB has helped them to link the theory and its applications more readily, due to the presence of extra information made available to them, besides the procedural instructions.

> What I like about the vLAB is they further elaborate on the reagents and procedures while you're doing the experiment, and I think that's very good because at least you know what you are doing and why you're doing it, but for live lectures, usually if you want to know more about your experiment, you have to do your further research on your own after the practical session. So that's one thing I learned from vLAB. (P19)

Students appreciated that vLAB could save time spent in science laboratories. They were able to complete the virtual experiments in a shorter time as the waiting time was reduced; hence, they could stay focused on the theory of the experiments.

> It's fast and uh… no clean-up... it avoids the mess, but still gives you the theory. (P9)
> Because I mean we can only be focused in like 15 minutes. So when we do that for 15 minutes …, we get all the knowledge and we don't feel like bored. (P14)

Learning Environment

Students commented vLAB provided an authentic learning environment, where the actual setting of the laboratory was simulated.

> All the information and knowledge from the virtual lab can be used in the conventional lab practical session because, …. all the things inside virtual lab is what we need in the next real practical. (P23)

The opportunity offered by vLAB to make errors without real cost or danger is perceived positively by students, as it helps students to learn through multiple attempts.

> I think we make mistakes then we will remember that clearly, so will know which part is doing wrong and then we can do some adjustment to that. (P20)

Individualisation of Learning

Individualised Learning to Personal Needs

All students appreciated the detailed first-hand interaction with the vLAB programme, where they can follow the entire procedure individually, unlike in physical laboratory sessions where the students often have to work in groups to save time and cost of conducting the experiments.

> It allows me to do it by myself, 'cause if in a in a real-life setting, I think I'll be in the group and sometimes work is distributed among all of us that I will miss up some steps. I won't see certain steps. But for this in the virtual lab, I'll be able to do everything step by step by myself'. (P13)

Besides that, vLAB allowed students to attempt the experiments multiple times before moving onto the physical laboratory later. Hence, they can go at their own pace and do not have to rush in vLAB. As a result, they had more time to reflect on their observations, identify the gaps and mistakes, and make an improvement, as well as relate to their prior knowledge.

> vLAB gives us the chance to redo that, unlimited time and also make us understand better on the concept and why we actually doing this. I think somehow it does enhance the conceptual understanding. (P1)
> Sometimes, like physical lab, it's really hard to pay attention because we have a time limit and we have to get our results within three hours. But with the virtual lab, we can take our time and also understand it at our own pace. (P14)

Areas of enhancement

User Experience

Nevertheless, some students commented on the user interface design of one of the recommended vLAB. It was not easy to use and pleasurable; hence, they could not get their tasks done smoothly. This has resulted in frustration and distraction and led to a negative impact on learning.

> Frustration and also some confused because I don't know whether I'm doing it wrong or do it right because you keep resetting. (P21)
> It gets away your attention because when it's laggy you don't want to re-do that thing anymore. So, I don't really like that part. (P6)

Feedback

The interviewees have given suggestions on some ways to make vLAB more effective. Decision making and rationalisation skills could be enhanced by having more options and room for mistakes which are followed by instant feedback. They also suggested opportunities for interactions with a lecturer in vLAB.

> I think if you let it proceed with some wrong steps then you give the correction after that. Like you give a protocol and you give him do it on on his own on the vLAB. Then after the vLAB, then you show him what he did wrong that I think you'll learn more by that. (P6)
> I would really love if there's another section for each step by step like if you have any further questions you can type in whatever your concerns so that the lecturer would know. (P8)

Collaborative Learning

Students also commented that they are performing the tasks alone and not able to learn together with their peers; hence, they were looking forward that vLAB has the capability for multi-users where they can have their peers in the virtual environment.

> You do a mistake, the lecturer will correct you. And then you will learn it...if your peers make a mistake, then lecturer corrects them and you can also learn. So

it's like learning from each other and we don't really see that in vLAB (P7)

Because vLAB, we will be doing individually. So rather than we thinking the problem alone, I think it's better to discuss with the groupmate or the lecturer (P20)

Discussion

Although there was no significant difference in the students' attainment of learning outcomes because of engagement in vLAB activities, the students nonetheless agreed that vLAB contributed positively to their learning. This study has revealed that vLAB is ideal in the context of constructive learning as it is an appropriate platform for students to construct their knowledge from meaningful immersive experiences by performing experiments in pedagogically structured virtual learning spaces. It activates the concrete experience and reflection observation components of Kolb's learning cycle, hence, activates the comprehension dimension because students can perform the experiment virtually. This is well supported by a study done by Abdulwahed and Nagy [17].

With the help of animation, vLAB enabled students to visualise the scientific phenomena that could be difficult or impossible to see and understand in the real world. Similar to previous studies, virtual laboratories can structure students' inquiry process and guide them through learning science [18, 19]. The majority of the students have also shared that vLAB assisted them to assimilate new information to their existing knowledge gained from lectures. Hence, vLAB could be used as a supplementary educational tool to enhance learning as they are authentic, economical, educational and engaging. Nevertheless, vLAB could not replace traditional laboratory completely, because psychomotor skills can only be obtained through physical hands-on activities. Therefore, it is recommended to complement vLAB with lectures and physical laboratory sessions as it reinforces both laboratory competency and conceptual understanding [20].

Our findings also indicated that vLAB supports individualised learning based on one's needs and learning space. As such, the students had sufficient time to engage in metacognitive activities, such as reflection that require further reading and inferring the central ideas of the experiment [21]. This could because vLAB is designed based on the pedagogy of the Kolb's experiential learning cycle, which could activate the comprehension dimension (Concrete experience-Abstract conceptualisation) among students hence facilitate constructivist learning, specifically reflective learning [22], that is hindered during physical practical sessions due to limitation in time, resources and logistical reasons. This is aligned with the pedagogical explanation of a previous study that showed enhancement of learning outcomes after an additional virtual laboratory session among bioscience students [23]. Moreover, students were able to revisit the experiment in vLAB without being restricted by cost, time, space and safety concerns. Hence, students were able to familiarise themselves with the experimental procedures and instruments and gain a better understanding of learning in the virtual environment. This could enhance the experimental efficacy among students about their ability to perform similar experiments in the physical laboratory later because vLAB has prepared the students for the physical laboratory experience, hence reduced their anxiety level, an affective factor that alters self-efficacy negatively [24, 25].

The Gagne's nine events of instruction were found to be applied in both vLAB sessions used as case examples in our study. For instance, the learning objectives were being conveyed at the beginning of the experiment and students were able to relate their prior learning with the newly learnt ideas to construct knowledge. In the virtual environment, students were free to explore the concepts and theories of the experiments, with guidance and additional tips without the worry of making mistakes. By the end of the experiments, students could elicit their understanding using quizzes. Hence, vLAB may be a better tool to prepare students for practical sessions in comparison to a face-to-face demonstration. This is in agreement with the study done by Makransky et al. that also showed virtual laboratory is as good as a face-to-face demonstration in a microbiology laboratory [26]. Our quantitative study also showed that vLAB is well perceived by all students, regardless of their learning styles, where the visual and auditory learners can achieve the learning outcomes by being able to see and hear the animated abstract processes in vLAB that are impossible to see or imagine. On the other hand, the incorporation of interactive flash animation in vLAB and the discrete cognitive load of vLAB engage kinesthetic learners to immerse and participate tactilely throughout the learning experience.

It is undeniable that vLAB can revolutionise the pedagogical model for teaching science, but the gaps in the actual applications still exist, especially from the technological point of view. Some students demonstrated non-favourable user experience and frustration with vLAB due to technical issues such as user interface, slow application performance, non-responsiveness, and lag time due to web-based applications overloaded by data. As a result, the learning process is affected as suggested by a report showing instances of confusion and frustration can have substantial impacts on learning [27].

The students suggested incorporating more feedback on their performance in vLAB. As shared by Harden and Laidlaw, feedback is essential to improve learning by modifying learner's thinking or behaviour [28]. In addition, students also look forward to an environment that allows rich interactions and collaborative learning with their peers in vLAB that promotes academic and social educational outcomes. As reported by Faulconer and Gruss (2018), there is a lack of collaborative learning in the virtual laboratory [10]. Hence, the application of socio-constructivist pedagogical models in vLAB may enable students to co-construct knowledge and foster higher-level thinking, in addition to interpersonal skills development and interprofessional learning among science students [29, 30].

Limitations

The delivery modalities of both health science programmes mainly use traditional classroom delivery. Virtual simulation is only used sporadically. Hence, two vLAB activities may not be sufficient to generate representative views of vLAB. The duration of the selected vLAB programs was short, which may not have a significant impact on the students' knowledge. Moreover, both selected vLAB experiments do not provide users with trial-and-error experiences, hence they may not improve problem-solving skills in answering the MCQs in pre-and post-tests.

Despite the participation in this study was open to all Year 2 and Year 3 MB and BM students, there was a possibility that the participants who volunteered were enthusiastic learners. Their perspectives may not be representative of all types of learners. We also acknowledge that the students' views may also be affected by their laboratory experience, whether individualised or group experience of doing a hands-on practical. In addition, the selected vLAB programs are from open sources, the data on frequency and duration of access is not available for further analysis. Nevertheless, the findings from the study are valuable for an understanding of how vLAB can be used to achieve learning outcomes. It contributes to the literature on instructional design and enhancement of vLAB.

Conclusion

In summary, our findings illustrated that virtual laboratory is well perceived by health science students. It is an appropriate educational tool with a constructivist approach and can be integrated into the teaching of science. vLAB prepared students for physical laboratory sessions by activating the comprehension dimension of the Kolb's learning cycle, hence enhance the attainment of laboratory outcomes.

Appendix. Questionnaire

Title: An investigation on the effect of interactive virtual laboratory simulation on learners' conceptual understanding of laboratory techniques

Thank you for spending your precious time to complete this questionnaire. This questionnaire serves as a means for us to solicit your conceptual understanding of the lesson you have completed. The results will be used to improve future teaching and learning. Your answers will be kept anonymous.

If you have any inquiries, you can email yihyih_kok@imu.edu.my or huimeng_er@imu.edu.my.

1-Completely disagree
2-Disagree
3-Neither agree nor disagree
4-Agree
5-Completely Agree

A	Opinion about vLAB	1	2	3	4	5
1	The interactive virtual laboratory simulation was easy to use					
2	The learning objectives were clearly defined at the beginning of the interactive virtual laboratory simulation					
3	I felt confident in using and navigating around the interactive virtual laboratory simulation programme					
4	I found the activities in the interactive virtual laboratory simulation were engaging					
5	Interactive virtual laboratory simulation helped me to visualize the concepts of PCR and DNA gel electrophoresis					
6	Interactive virtual laboratory simulation stimulated my interest to search for additional information					
7	Interactive virtual laboratory simulation stimulated me to recall my prior knowledge about PCR and DNA gel electrophoresis					
8	Interactive virtual laboratory simulation guided me through the steps in the experimental procedure					
9	The interactive virtual laboratory simulation helped me to retain my knowledge of PCR and DNA gel electrophoresis					

A	Opinion about vLAB	1	2	3	4	5
10	Making mistakes in the interactive virtual laboratory simulation helped me to learn the experimental procedure					
11	I felt safe to make mistakes in the interactive virtual laboratory simulation as I could repeat as many times as I liked					
12	The interactive virtual laboratory simulation provided feedback to me when I made mistakes					

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Author Contribution YYK, HME, and VDN conceptualised the work, designed the study, interpreted, and analysed the data. YYK contributed to the acquisition of data. All authors had full access to the data, contributed to the study, and approved the final version for publication.

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Availability of Data and Material Data are available on request to the authors.

Declarations

Ethical Approval The study protocol was approved by the International Medical University Joint Committee on Research and Ethics.

Consent to Participate The study objectives and details of the project were explained to participants during synchronous Microsoft Teams sessions, and written consent was obtained from the participants before data collection. Informed consent to participate in the study was obtained from all participants.

Conflict of Interest The authors declare no competing interests.

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