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RESEARCH ARTICLE

Enhancing Biology Laboratory Learning: Student Perceptions of Performing Heart Dissection With Virtual Reality

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ABSTRACT In this study, we investigate the attitudes of students towards an immersive educational instruction method used to augment in-person biology laboratories. Specifically, we employ the Oculus Quest 2 in a mid-sized biology classroom setting to conduct a virtual heart dissection instructional class using Virtual Reality (VR). We engaged with 23 students from a Singaporean secondary school to gather insights into their experiences and perspectives. The focus of this study is twofold: firstly, to assess the potential of VR technology, particularly the Oculus Quest 2, as a tool for enhancing learning in biology, and secondly, to evaluate the feasibility of replacing traditional in-person laboratory settings with VR-based learning environments. By examining the students' experiences, this research sheds light on the effectiveness of VR technology in enhancing academic engagement and understanding of this specific content taught in a standardized biology syllabus. Our findings reveal that Oculus Quest 2 with VR can significantly stimulate student interest in this topic. The study provides insights into how VR as part of educational technology can transform the traditional learning experience, offering a more interactive and engaging approach to education in biology. These preliminary results have important implications for the future of educational methodologies in science and technology subjects.

INDEX TERMS Virtual reality, biology laboratory, immersive technology, visualisation, Oculus Quest 2, biomedical engineering.

I. INTRODUCTION

Biology represents a distinctive facet of the natural sciences. Yet, akin to other natural sciences, it shares the common goal of delving deep into the comprehension of natural phenomena and occurrences. Within biology, two primary domains come to the fore: functional biology and historical biology, the latter of which is often referred to as evolutionary biology [1]. Challenges within the realm of natural sciences form an integral component of a well-rounded curriculum. A profound comprehension of these challenges not only aids students in making informed career choices but also contributes to the cultivation of an educated society and sustainable development [2].

An array of biological topics, including cell structure, botany, zoology, and human anatomy and physiology,

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are introduced as early as elementary school, albeit at a fundamental level. In secondary school, these subjects are explored in greater depth, fostering increased student engagement. Bridging theory and practical applications is of paramount significance [3]. Čipková et al. noted a strong enthusiasm for Biology among most students who favor active and hands-on engagement in the learning process. This is achieved through the study and exploration of living organisms, as well as the practical execution and evaluation of experiments [4].

The absence of a foundational understanding of autecology may hinder students from establishing meaningful connections between abstract concepts like those found in systems ecology (such as matter cycling) and the natural world, as well as comprehending how their digestive system, for instance, plays a role within a broader food web and energy flow [5]. Similarly, a thorough understanding of the structures of the heart is essential for students. This enables them to comprehend the functioning of the human heart and the intricacies of blood circulation. Pedagogically, the lessons learned from studying the biology of the heart can also be translated to understanding other biological systems, and thus are foundational for advanced biological studies. Furthermore, analyzing the complex structure and function of the heart helps develop critical thinking and problem-solving skills, which are valuable in other scientific or academic pursuits. However, the study of real human or animal hearts ex vivo is limited for learning the physiological mechanisms of the human heart in vivo. The integration of technology serves to enhance their learning, facilitating a more profound grasp of the subject matter that is likely to be retained in their memories for an extended period [6], [7]. Thus, this study will investigate students' experiences with incorporating technology into Biology education.

In recent years, virtual reality (VR) and augmented reality (AR) applications have rapidly emerged as highly effective tools, providing users with the opportunity for visual interaction with virtual objects [8]. There has been a surge in the availability of high-quality consumer VR equipment in recent years like the HTC Vive, Oculus Rift, and Oculus Quest. VR simulations have a long history of application, especially in fields like flight and medical simulations, providing a secure means to gain experience in high-risk scenarios [9]. These VR environments create a strong sense of presence by delivering immersive experiences [10]. Furthermore, numerous studies have demonstrated the beneficial impact of incorporating VR technologies into academic pursuits [11], [12], [13]. This holds particular promise for biology education, where there exists a demand for intuitive and top-tier 3D visual representations for abstract topics like molecular structures or studying internal organs [14].

There are studies that involve the use of VR in education, such as Cellverse. Cellverse is an educational game, designed as a cross-platform VR project for high school biology students. Its primary objective is to instruct students about the structure and functions of cells. In this interactive experience, two players collaborate to investigate the intricacies of a human lung cell and address a potentially life-threatening genetic condition. The creation of Cellverse can be attributed to the innovative efforts of the Collaborative Learning Environments in Virtual Reality (CLEVR) team [15]. In another investigation, VR videos were disseminated to students enrolled in an undergraduate junior-level bio-molecular engineering laboratory course. These videos covered laboratory procedures, experiments, and theoretical content, enhancing the bio-molecular engineering curriculum [16].

Furthermore, VR technology has found diverse applications in the biomedical field. There are studies that have utilised VR in laparoscopic skills training, evaluating whether video-based coaching can enhance laparoscopic skills performance [17]. InsectVR is a VR platform crafted for biology edutainment. It simulates crawling insects within realistic and immersive virtual environments, aiming to enhance user's understanding of these fascinating creatures [18].

Examination of heart specimens have significantly contributed to establishing a foundational understanding of cardiac anatomy, a topic within secondary school biology. A study used three-dimensional images based on the volume-rendering method to depict the heart anatomy [19]. The dissection of the mammalian heart in secondary biology classes can extend beyond merely exposing the internal structure and function of the heart. It offers an opportunity to illustrate crucial aspects of blood circulation, such as the blood supply to the heart, and insights into the causes and consequences of coronary heart disease [20]. Cross-sectional anatomy poses challenges for both students and educators due to the intricate topographic relationships among structures and their associations with body levels. To address this difficulty, a study integrated clay modeling into gross and neuro-anatomy courses to facilitate students' understanding of cross-sectional anatomy [21].

However, when generating three-dimensional images using the volume-rendering method, it is crucial to bear in mind that the quality of the final image is contingent upon the quality of the raw data [19]. However, utilising clay models for anatomy learning may not be as effective due to its time-consuming nature, especially when considering the level of detail involved [21]. To ensure a clearer and more accessible presentation of the heart's anatomy for students, and to enable compatibility across multiple devices within a shorter timeframe, we suggest opting for VR lamb heart dissection as an alternative. Just as VR has been instrumental in supporting students' understanding of abstract concepts such as partial derivatives in multivariable calculus [22], our application aims to similarly enhance the grasp of intricate biological phenomena, underscoring the versatility of VR in education.

To explore students' experiences with a VR lamb heart dissection application that enhances their understanding of heart structures in biology, we conducted our study with Secondary 3 students, aged 14-15 from a public secondary school in Singapore. We developed a virtual lamb heart dissection app using Unity, an open-source software. This software allows us to create an Android Application Package (APK) that can be installed on the Oculus Quest 2 for our research purposes. Unity offers an extensive library of resources that streamline the application development process, and developers can also source assets from various websites, reducing the need to create everything from scratch.

The main objective of this app is to replicate the experience of dissecting the heart of a lamb. This is part of the standardised curriculum that a student will typically participate in during a laboratory session. However, due to the challenges posed by the COVID-19 pandemic, students were unable to attend in-person laboratory sessions. Therefore, we aim to provide students with the opportunity to experience virtual dissection in the event of future pandemics or similar disruptions. Our work here also extends the concept of integrated virtual laboratories [23], [24], to the biological sciences, showcasing the interdisciplinary utility of VR-based learning environments.

In this paper, we embark on a comprehensive exploration of the applications and educational approaches in the realm of biology, with a specific focus on cardiac anatomy. In Section II, we outline our choice of hardware Oculus Quest 2, followed by Unity, the platform on which the entire application was built. Next, in Sections III and IV, we present our research methodology and discuss the results. We conclude in Section VI.

II. TECHNOLOGICAL INFRASTRUCTURE

A. HEAD-MOUNTED DISPLAY HARDWARE: OCULUS QUEST 2

The Oculus Quest 2 Head-Mounted Display (HMD) equipped with two controllers was specifically chosen as the headset for developing the virtual lamb heart dissection due to its immersive and interactive environment. Similar to the utilization of Google Cardboard VR for visualizing multivariable calculus concepts [25], our study leverages the Oculus Quest 2 to enhance the visualization of biological structures, demonstrating the cross-disciplinary applicability of affordable VR technologies in complex subject matter comprehension. Before the introduction of the Oculus Quest, six-degrees-of-freedom (6-DoF) tracking was confined to hardware dependent on costly PCs and their corresponding graphics processors. With an exclusive software ecosystem and multiplayer support, this type of virtual reality (VR) experience represents a leap beyond the 360-degree stereoscopic video experiences commonly utilised by educators in the past [26]. 6-DoF tracking defines the pinnacle of the VR experience. This technology is potent because it allows users to navigate through a virtual scene and explore a digital environment in all directions, akin to their movements in a physical environment. Unlike the simple act of turning one's head, as seen with 360-degree video on Google Cardboard unit, 6-DoF tracking enables users to traverse a scene and discover its contents in real time. The Oculus Quest, with its stringent performance benchmarks set by the Oculus marketplace and the AI-powered "inside out" tracking system (eliminating the need for extra tracking hardware such as HTC Vive), stands as the first standalone, fully functional VR system [26].

As the Oculus Quest 2 runs on Android Operating System, our team opted to develop an Android Application Package (APK) to be installed on the Oculus Quest 2 for this study. This decision was made to enable us to run the application on the Oculus Quest 2 without commercialising it, allowing for cost-efficient testing with students. Since there is a readily available build setting within Unity, developers can connect the headset to the laptop using a USB-C cable that comes with the Oculus Quest 2 to build it into the VR headset. Once the APK is completed within Unity, it can be built into different sets of Oculus Quest 2 or other headsets that support the system settings as the APK that was developed.

B. VIRTUAL REALITY SOFTWARE: UNITY

Unity is a versatile game engine engineered to create and support 2D and 3D video games, computer simulations, virtual reality experiences, as well as content for consoles and mobile devices. This commercial software is developed by Unity Technologies. Unity 3D empowers users to engage in three-dimensional manipulation and simulation through the utilisation of programming languages to define functions [27]. GitHub was used to manage our application updates and facilitate collaboration among the development team.

The development of the heart dissection VR app is summarised in four stages: (a) constructing all the 3D model with Blender 3D computer graphics software (www.blender.org), (b) creating the entire app in Unity including user interface information, (c) installing the application as an APK file, and (d) executing the application through the VR system. Blender, an all-encompassing, free, and open-source 3D creation suite, spans the full range of 3D production tasks, including modeling, rigging, animation, simulation, rendering, compositing, motion tracking, as well as video editing and game development[1]. In the initial stage, a 3D lamb heart model is crafted using Blender. Moving to the second stage, the model is placed into Unity, and the entire app is created within Unity. Following this, the APK file is installed onto the VR headset Oculus Quest 2 as part of the third step. The final stage involves executing the APK file within the VR Oculus Quest 2 environment. The VR content and pedagogical strategies were tailored to align with the existing curriculum. This alignment ensured that the VR environment served as an effective tool for facilitating immersive learning experiences, thereby enhancing students' understanding, retention, and application of scientific concepts. The curriculum was developed through iterative collaboration with educators, ensuring the tools' relevance and effectiveness for the intended learning outcomes.

[1]https://www.blender.org/

We initiated the app development process by establishing the laboratory environment, which was acquired from the asset store. The whole laboratory environment is illustrated in Figure 1. By incorporating the complete laboratory setting, we aim to simulate a realistic and immersive learning environment, enhancing the overall educational experience [28]. Additionally, the inclusion of the entire laboratory environment allows for a comprehensive analysis of how VR technology can be seamlessly integrated into traditional educational settings, offering insights into its potential impact on students' engagement and learning outcomes [29].

FIGURE 1. The view from behind of the developed entire laboratory environment.

Figure 2 captures a moment during the VR biology lesson, depicting an immersive 3D classroom environment. A virtual human heart model is seen in the foreground, held in place by a user's avatar. Prominent on-screen text guides the student through the steps following a dissection procedure. Figure 3 showcases a different stage of the VR dissection process, where the user is directed to "cut along the dotted line". This directive is part of a series of instructions provided to students on how to proceed with the dissection of the virtual heart model. These steps are critical in teaching students the proper technique and sequence of dissection, which are important skills in biological studies. The VR environment is consistent with that of a well-equipped classroom, creating an engaging and contextualized learning experience. These screenshots illustrate the detailed and interactive instructional design of our VR application, highlighting the technology's capability to provide step-by-step procedural guidance in an engaging and controlled virtual environment. In the course of our design methodology, we crafted a model of the heart using Blender 3D software. This model is specifically engineered to be bisected, facilitating an interactive exploration of the heart's internal structures for educational purposes.

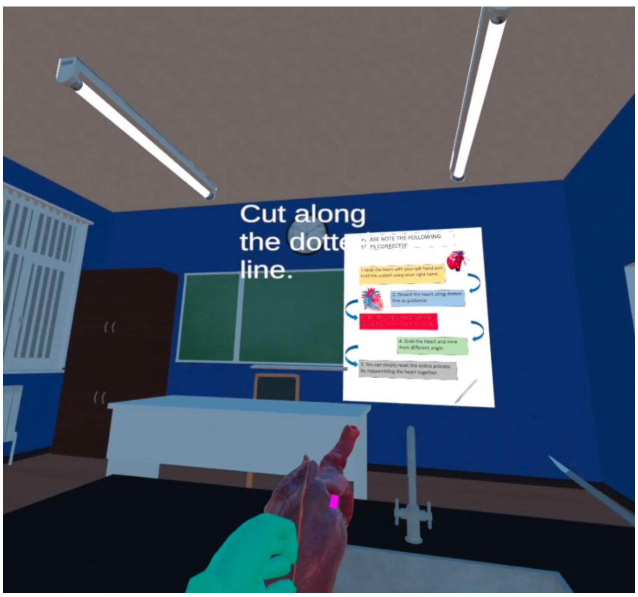


FIGURE 2. This screenshot presents a user in the process of a virtual heart dissection, following on-screen prompts within the VR classroom. The current instruction 'Cut along the dotted line' guides the user in making precise incisions on the heart model, illustrating the next step in the interactive learning sequence.

FIGURE 3. This screenshot captures the VR simulation, where users are guided with clear on-screen instructions to place the scalpel back on the left tray. This facilitates an organized approach to learning the procedural aspects of heart dissection within the virtual lab setting.

Pertaining to the heart's cross-sectional view, the interactive model enables users to discern and label crucial anatomical components—including the aorta, left atrium, right atrium, left ventricle, right ventricle, and the apex–subsequent to the digital dissection process, as depicted in Figure 4.

The app was designed with instructions located beside the left controller of the Oculus Quest 2, instructing users to hold the heart in their left hand at the beginning. Once the user grasped the heart with their left hand, the next instruction prompted them to pick up the scalpel using their right hand and then dissect the heart by bringing the scalpel near the lamb heart model. After dissecting the heart, users were guided to place the scalpel on the plate to the left. Following that, small boxes appeared on the left half of the lamb heart model in Figure 5. Users could grab the labels from the middle plate and release them onto the corresponding boxes.

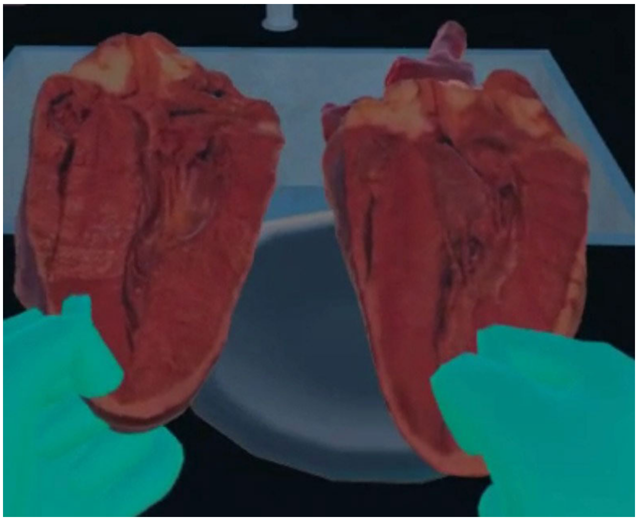


FIGURE 4. Cross-sectional view of the heart model after cutting into half.

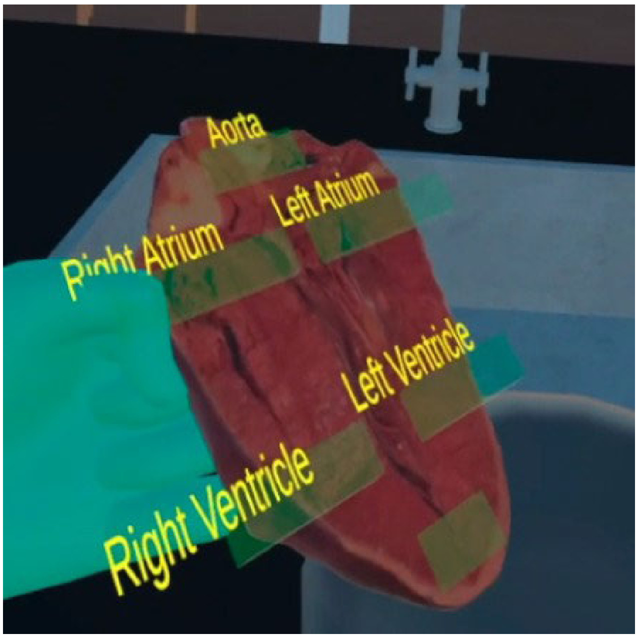


FIGURE 5. Example of labeling boxes on the left side of the lamb heart model. This immersive labeling task enables students to identify and learn about the different parts of the heart in a hands-on virtual environment.

If they placed a label incorrectly, users were allowed to grab and reposition it in the correct box. Once they had completed the labeling, users could press the button 'A' on the right controller to view the correct answers for labelling. In case users missed the instructions, they could refer to the whiteboard in the laboratory as shown in Figure 6.

III. EXPERIMENTATION AND EDUCATIONAL RESEARCH

Initially, we conducted a 10-minute introductory session to familiarize students with the VR environment. Following this, they were allotted 20 minutes to independently explore the VR experience. Our VR developer and engineer were on-site to address any questions from the students. Before allowing the students to begin their exploration, we offered guidance on operating the VR app on the Oculus Quest 2 to ensure a smooth experience. For example, we briefed them on how to select and grab objects as well as identified the objects available for manipulation in VR. Additionally, we informed them to follow the instructions displayed beside the controller or on the whiteboard. We also included a video depicting the actual simulation before its utilisation as shown in Figure 7. In our Appendix, the online repository encompasses a diverse array of materials aimed at enriching the educational experience within our VR Biology Heart Dissection module, specifically tailored for the Oculus platform. The resources included are meticulously designed to ensure a smooth and informative learning journey for students, comprising:

1) Detailed video instructions alongside a captivating preview of the VR Biology Heart Dissection experience, designed to give students a comprehensive

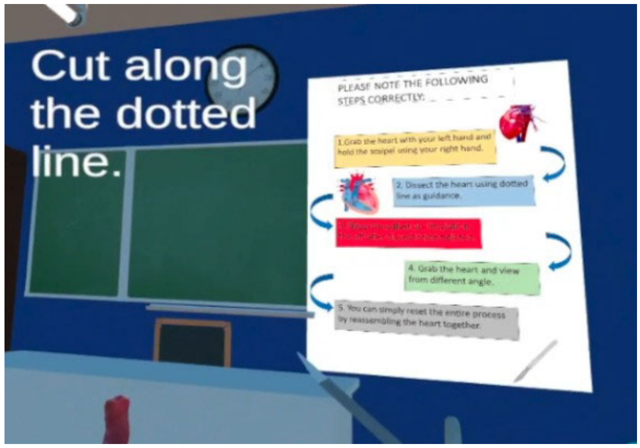


FIGURE 6. Instruction that appeared beside the controller and on the whiteboard.

FIGURE 7. The VR engineer briefing the students about the operation of the Apk through a video.

understanding of what to expect and how to navigate the virtual lab environment.
2) A set of explicit instructions for the students, which serves as a step-by-step guide to facilitate their engagement with the VR content, ensuring they can maximize their learning outcomes while navigating through the heart dissection simulation.
3) A carefully curated deck of briefing slides intended for students, which aims to provide an overview of the learning objectives, key concepts to be explored, and an introduction to the VR technology used in the course. This material is crafted to prepare students mentally and academically before they embark on the VR dissection exercise.

Each component within this repository is integral to the educational framework of the VR Biology Heart Dissection course, ensuring that students are well-prepared, informed, and capable of providing insightful feedback on their learning experience.

It was emphasized that the entire simulation would reset if the heart was accidentally dropped on the 'floor'. This feature was implemented so that students can reset the entire simulation if they choose to. To offer support, we had a few engineers on standby to provide assistance in case students encountered any difficulties as shown in Figure 8.

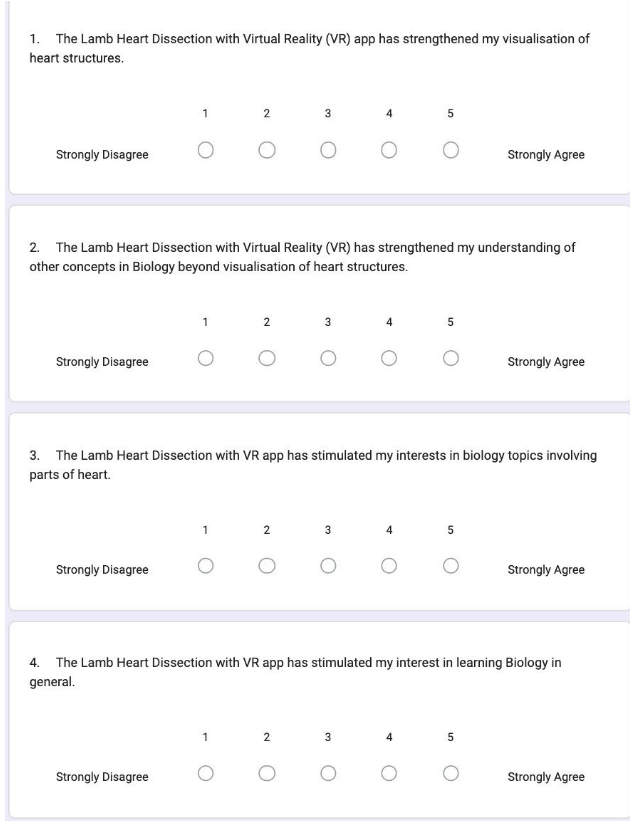
FIGURE 8. The VR engineer assisting the student in setting up the headset.

Most students thoroughly enjoyed the VR session when we introduced them to the VR app on Oculus Quest 2. Both Figure 9 and Figure 10 demonstrate students using the Oculus Quest 2 to explore the virtual lamb heart dissection application. It is evident that they were fully immersed within the virtual world.

FIGURE 9. Students engaging with the virtual lamb heart dissection application using Oculus Quest 2 during the VR sesion.

We incorporated survey questions that comprehensively evaluated the following constructs: "Visualisation", "Stimulating interest in the topic and academic subject", "Confidence", "Supplementing physical classroom", "Replacing physical classroom" and "Perceived usability" [30], [31]. For "Visualisation" and "Stimulating interest in the topic and academic subject", two 5-point Likert scale questions with 1 = strongly disagree, 3 = neutral, and 5 = strongly agree were included as shown in Figure 11. "Confidence", "Supplementing physical classroom", and "Replacing physical classroom" each featured one Likert scale question, accompanied by an additional open-ended question for "Replacing physical classroom". Additionally, the "Perceived usability" construct encompassed 11 Likert scale questions. This survey specifically designed to collect feedback from students regarding their experiences with the VR Biology Heart Dissection can be found in our Appendix. This feedback is invaluable as it helps in assessing the effectiveness of the VR educational tool, identifying areas

FIGURE 10. The student was fully immersed in the virtual world.



1. The Lamb Heart Dissection with Virtual Reality (VR) app has strengthened my visualisation of heart structures.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

2. The Lamb Heart Dissection with Virtual Reality (VR) has strengthened my understanding of other concepts in Biology beyond visualisation of heart structures.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

3. The Lamb Heart Dissection with VR app has stimulated my interests in biology topics involving parts of heart.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

4. The Lamb Heart Dissection with VR app has stimulated my interest in learning Biology in general.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

FIGURE 11. Example of survey questions for visualisation and stimulating interest in the topic and academic subject constructs. The rest of the survey questions can be found in our appendix.

for improvement, and enhancing the overall quality of the learning experience.

IV. RESULTS AND DISCUSSION

In this study, there were a total of 23 survey responses that were gathered from Secondary 3 students. The mean values for each construct measured among Secondary 3 were computed, as shown in table 1. Notably, all the mean values for each construct are higher than a neutral response of 3. Among them, the "Stimulating interest in the topic and academic subject" emerged as the highest-rated construct, with a mean value of 4.17.

TABLE 1. Average of each construct for secondary 3 biology students.

Construct	Mean	SD
Visualisation	3.891	0.8785
Stimulating interest in the topic and academic subject	4.174	0.8063
Confidence	4.043	0.8245
Supplementing physical classroom	4.130	0.9197
Replacing physical classroom	3.130	0.8149
Perceived usability	3.648	0.6155

The higher rating of 4.17 for "Stimulating interest in the topic and academic subject" suggests that the VR experience was particularly effective in stimulating interest through the immersive environment provided by VR. This positive response is a notable strength of the VR intervention in stimulating interest in students studying Biology. Participants expressed a relatively high level of "Confidence" with an average of 4.04 in the VR learning experience. However, while many of the students found this approach of learning beneficial, they also pointed out the pedagogical enhancements that are needed for a fully implementable VR system to augment laboratory classes. For instance, students mentioned that 'VR enables hands-on experience while textbooks and PowerPoint [are] more fixated on the content', 'VR feels more fun', and '[I]n the classroom we can only see 2D pictures however we can experience the "actual" thing in VR'. However, some students highlighted concerns ranging from '[I]t is laggy', '[T]his is fake but [the] textbook is more real and physical', '[C]onventional learning can be used for longer periods of time' and 'Conventional classroom setting is less fun, but more detailed'. These sentiments are captured in the lower score for the "Visualisation" aspect of the VR experience at 3.89.

Following closely, the "Supplementing physical classroom" construct garnered an average values of 4.13. In contrast, "Replacing physical classroom" exhibited the lowest mean value among all constructs, scoring 3.13. The rating for "Supplementing physical classroom" suggests that the VR experience was perceived as effective in supplementing the physical classroom. It implies that participants found value in the VR tool as a supplementary educational resource. The lower rating of 3.13 for "Replacing physical classroom" indicates that participants may not view the VR experience as a complete substitute for traditional classroom learning. This could be due to various factors, such as the importance of in-person interactions in a classroom setting.

Next, "Perceived usability" attained a slightly higher mean value of 3.64. This rating suggests a slightly higher level of user-friendliness. Exploring specific aspects that contributed to this rating, such as navigation or interface design, could guide improvements in usability. Students indicated that despite providing instructions on how to operate it before the VR session, some found it challenging to control. This could be addressed by incorporating a video featuring a real person operating the VR app or holding the Oculus Quest 2 controller while giving instructions, enhancing clarity. While a few students could understand and operate the Oculus Quest 2 easily without issues, others faced a problem relating to orientating themselves in the virtual environment. Additionally, some participants provided feedback, mentioning the difficulty in grabbing the heart and scalpel, possibly because they were unaware that they could use the line pointed out from the controller in VR to grab objects from a distance. In future, it is essential to ensure that users understand clearly how to grab objects. One student reported blurry words, which might be attributed to the wearing position of the Oculus Quest 2 headset; however, others had no issues with the text. With developers on-site to assist students in optimising the headset position including tightness, others found the text comfortable to read. Lastly, a few students noted occasional lag, although, during app development testing, there was no experience of lag. We suspect that this might be due to application optimization. If this is the case, the issue could be addressed by optimizing the app to ensure it does not consume excessive memory space.

Our investigation also aligns with the findings from two review papers on the adoption of VR and AR [32], [33], indicating a growing trend towards integrating immersive technologies across STEM fields to facilitate a deeper learning experience. Finally, while the VR experience primarily suggests an advantage in stimulating interest and fostering confidence to supplement classroom teaching, there are specific areas such as visualisation and usability, where enhancements might be considered.

V. FUTURE WORK

Some students provided feedback indicating difficulty in grabbing labels easily. This challenge could be addressed by either increasing the size of the labels or implementing a ray-casting method, where a line extends from the controller to the object, allowing users to point at the object and press the grab function button on the controller. Since this was the first time students used the Oculus Quest 2, they initially attempted to grab objects by bringing the virtual hand closer to the object, unaware that they could use the ray-casting method for grabbing. On the other hand, we could provide detailed instructions on how to grab objects within the VR (beyond informing them which button to use for object manipulation).

Echoing the didactic explorations in mathematics education [34], our VR application harbors the potential for evolving biology classrooms into spaces of enhanced peer learning and teacher-guided exploration, and this motivates future work. Future investigations would also benefit from expanding the sample size to enhance the generalizability of the findings. Additionally, subsequent studies could explore the implications of using simulated tools like virtual scalpels on students' perceptions and behaviors towards safety and risk when transitioning to real-world lab environments. Such research could help in developing integrated educational approaches that combine the safety of virtual tools with effective risk-awareness training for handling real instruments

VI. CONCLUSION

In this study, we have evaluated the experiences of students engaging with a VR application specifically designed for the dissection of a lamb's heart, within the broader educational domain of biology. This innovative approach not only addresses the significant costs associated with procuring real lamb hearts for educational purposes but also navigates the ethical considerations tied to the use of animal specimens in educational settings. The empirical evidence, drawn from a cohort of twenty-three Secondary 3 students through meticulously designed survey instruments, consistently revealed a broadly positive reception towards this novel educational tool. The VR application was particularly lauded for its capacity to significantly enhance students' interest in both the specific subject matter and academic study more broadly. Furthermore, it was recognized for its ability to augment traditional classroom instruction and bolster students' confidence in engaging with the curriculum.

This study's outcomes underscore the considerable promise held by VR technology as an adjunct tool in the domain of biology education, offering a richly immersive and interactive learning experience that traditional methodologies may not fully replicate. However, participant feedback illuminated several areas for improvement, notably concerning the application's visual presentation, usability, and the nuanced balance between virtual and physical learning environments. These insights are instrumental in guiding the refinement of the VR application, underscoring the critical need to hone specific elements such as user navigation and interface design to bolster the application's overall usability and effectiveness.

The evidence garnered from this study strongly supports the assertion that VR technology can serve as a potent supplementary resource in the educational toolkit, particularly within the realm of biology education. By addressing the highlighted areas for enhancement, based on participant feedback, educators and software developers are well-positioned to exploit the inherent strengths of VR technology, thereby enriching the educational journey for students.

The insights derived from this research contribute valuable perspectives to the ongoing evolution of technology-assisted educational methodologies.

To build upon the foundational findings presented herein, we advocate for the initiation of further investigative endeavors aimed at refining the VR application in alignment with student feedback. A subsequent phase of research could involve a longitudinal study design, meticulously tracking the evolution of student perceptions and academic performance over an extended timeframe. Such a methodological approach would afford deeper insights into the longitudinal impact of integrating VR technology into the biology curriculum, specifically as it pertains to the dissection of a lamb's heart, thereby illuminating the trajectory of students' engagement and comprehension facilitated by this innovative educational tool.

APPENDIX

(i) The video presentation and preview of our VR biology laboratory, designed for use within the Oculus platform, is comprehensively detailed in https://osf.io/mh7kz/?view_only=a0abeffa3c1b4ae0bc746d2151a21775.

(ii) Additionally, the above online repository includes a thorough set of instructions intended for student use, ensuring they are well-prepared and informed before engaging with the VR lab experience.

(iii) To further facilitate understanding and readiness, a deck of briefing slides, specifically curated for student briefing purposes, is also provided within the online repository.

(iv) A survey specifically designed to collect feedback from students regarding their experiences with the VR Biology Heart Dissection can also be found in the online repository.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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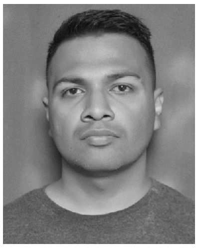

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