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From concept to reality: the use and impact of 3D prints as academic tools for high school biology education

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ABSTRACT

While Science, Technology, Engineering, and Mathematics (STEM) education is essential in the high school curriculum, it often carries a reputation of being formidable and overwhelming. The resulting unease students often face inhibits their ability to learn effectively; thus it can be beneficial to integrate a more familiar approach to teach them such complex topics. We have developed a technology-enabled learning environment surrounding the use of 3D prints focused on the topics of homoeostasis and immunity for a ninth grade Living Environment class. The teacher and students' surveys reveal that the 3D prints helped the students to effectively learn the material leading to a better understanding and retention of the topics. The results from the students' performance, as well as the teacher and students' feedback from the activity, demonstrate the effectiveness of 3D prints on maintaining their interest through a student-centred, student-led learning activity.

KEYWORDS
Education; learning; interactive technology; high school science; virus 3D models; living environment class

Introduction

Conventional teaching methods of recent decades are heavily based on textbooks and lectures, often referred to as 'frontal teaching', or 'chalk-and-talk' (Heaysman and Tubin 2019; Mingming 2019; Snyder 1999). However, students of today's generation have a strong inclination towards technology-enabled learning due to its high prevalence in modern society; consequently, our educational system must change with them. Research shows that this student generation no longer learns through reading or listening; they learn by doing, and it is therefore imperative to teach through movement and activity (Lacey 2010; Reid 1987; Stewart et al. 2017; Trembach and Deng 2018). This specific teaching approach is referred to as experiential learning, or total physical involvement with a learning situation (Nancekivell, Shah, and Gelman 2019; Reid 1987; Saga, Qamar, and Trali 2015). Enhanced engagement, communication skills, and critical thinking have been proven to be found in students whose 'educators deviate from the traditional pedagogy of didactic, content-driven teaching to a concept-based, student-centred approach using active learning activities' (Wagner 2014). These findings are most prominent in students learning subjects in the Science, Technology,

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Supplemental data for this article can be accessed here.

Engineering, and Maths (STEM) fields (Christensen et al. 2018; Keaveney et al. 2016; Schelly et al. 2015; Tillinghast et al. 2014; William, Erin, Gabrielle, & Amy).

A method of technology-enabled learning that has made notable advances in recent years is Three-Dimensional (3D) Printing, which first emerged in the engineering field (Quincy & Jamika ; Tillinghast et al. 2014; Wendt, Wendt, and Beach 2015). It produces 3D objects by adding layer upon layer of materials based on a virtual or computer-generated model of the desired object (Jakus 2019; Lim et al. 2016; Ngo et al. 2018). The recent emergence of 3D printing technologies allows for facilitated opportunities for improved teaching practices in a range of subjects and educational settings, as 'its ability to directly manufacture complex objects using high resolution digital data allows bypassing of conventional manufacturing processes to producing highly accurate models, in less time and at a reduced cost' (Ford and Minshall 2019; Jakus 2019; Lim et al. 2016; Ngo et al. 2018). Digital fabrication technologies such as 3D printing can lead to educational activities that allow for tangible representations of abstract and complex scientific ideas.

The handling of objects that 3D printing enables falls within the theories of object-based learning (Atif, Benlamri, and Berri 2003; Chatterjee 2011; Schultz 2018; Smith 2016). Although there are students who are able to picture 3D objects in their minds, this is not the case for all students, and especially those who have not had previous exposure to the topic at hand. Object-based learning is an approach that actively and strongly integrates objects into the learning environment. This approach is especially important when 'mental rotation' is required, which is often the case with many STEM subjects. Many concepts in the science field require the development of complex, cognitive 3D mental rotation skills, yet traditionally the knowledge required to attain these skills is presented in a textbook or PowerPoint presentation–both of which are heavy in text and 2D pictures. This can impact student engagement, as more superficial content can be taken as a didactic and passive transfer of information. Instead of passive learning, the object-based approach allows students to shift to an active learning style in which they develop their understanding through interaction. The teacher acts only as the facilitator as the students' interactions are focused on themselves and the object at hand, enabling them to explore processes related to the object and further link these processes to more complex and abstract concepts (Atif, Benlamri, and Berri 2003; Chatterjee 2011; Schultz 2018; Smith 2016).

3D printing has previously been used in various educational settings, including public schools, universities, and special education settings (Buehler et al. 2016; Chien and Chu 2018; Tillinghast et al. 2014). The integration of 3D prints into curricula has shown that by creating tangible representations of abstract concepts and therefore demonstrating their legitimacy in a real-world setting, the lessons are of more value to the students, increasing their interest and performance with the subject (Hsiao et al. 2019; Tillinghast et al. 2014; William et al. 2017). By adapting to the object-based approach, the educators shift the classroom setting into a student-centred learning style (Connell, Donovan, and Chambers 2016; Fernandes and Simoes 2016; Francke and Alexander 2018), involving the balance of power moving from the lecturer to the student. As the students turn from passive consumers into active and creative users, they learn to assimilate, apply, and describe new knowledge more effectively (Fidalgo et al. 2019; Loy 2014; Rias et al. 2017). Combining students' positive outlooks on the use of technology in the classroom with the learner-centred education style and visuospatial representations of the complex, 3D prints hold the potential to create a learning environment optimal for STEM success.

The specific purpose of this work is to explore the effects of 3D printing on a high school biology class. Due to the nature of biological sciences and the type of information present, learning the subject is heavily based on memorisation. Biology includes many abstract concepts, events, topics and facts that students have difficulty learning (Chiappetta and Fittman 1998; Çimer 2012; Connell, Donovan, and Chambers 2016). In addition, the curricula are often overloaded due to the amount of material present in the subject; excess of abstract, interdisciplinary information prevents students from learning biology effectively and renders them unmotivated, with a negative attitude towards the subject (Çimer 2012; Rosenzweig and Wigfield 2016). Moreover, students often do not understand why they are learning certain topics or concepts in biology because they cannot connect them with their real lives. A lack of understanding of the reality of their studies leads to a natural disengagement with the subject. Lastly, most educational providers believe student-centred learning of biology would be ineffective due to the amount and type of material present, so most lessons are taught via a teacher-centred style (Çimer 2012; Hewson et al. 1999). As a result, biology lessons become boring and uninteresting for the students, negatively affecting both their learning of and attitude towards the material (Cheon and Reeve 2015; Legault, Green-Demers, and Pelletier 2006). We recently implemented gamification into high school biology that successfully improved the students' attitude and performance with the subject. Kahoot! was used to test their understanding in a fun and competitive way, allowing the students to learn from each other rather than solely from a textbook (Jones et al. 2019). Our goal was to build on this work and make learning biology more enjoyable by reconnecting students to the reality of their studies via a student-centred learning environment, involving the use of 3D prints.

Methods

The 3D models were obtained from an online free 3D printing website, Thingiverse (Thingiverse 2013–2017). Another file consisting of 10 infectious pathogens, including Human papillomavirus (HPV) and Dengue, was also downloaded on Thingiverse, along with a file of bacteriophage T4 models (Thingiverse 2013–2017).

Once the design files were downloaded, Ultimaker Cura version 3.6.0 was used to create an STL file. All of the models were printed using the Stratasys FDM Elite (Stratasys 2019).

The STL files were opened on CatalystEX version 4.5 to lay out the models and to prepare them for printing [Supplementary Materials, 1]. The models were printed using soluble thermoplastic support material and were given a total of 50 hours to print.

For the antigen-antibody models, the receptors had magnets placed in them to demonstrate the antibody–antigen interaction. Using a 3 mm drill bit, two holes were drilled into the Immunoglobulin-G (IgG) receptors, and one hole was drilled into the antigen receptors. Two 3 mm X 1 mm Neodymium disk magnets were glued into the holes of the IgG and antigen receptors using fast-drying modelling glue.

To accompany the 3D models, a sheet that included descriptions of the viruses and another one that had descriptions of the antibodies and antigens were created. A 10-question quiz was designed using past New York Regents Living Environment Exam questions on the topics of homoeostasis and immunity to not only test the student's knowledge before and after the activity but to also prepare them for the Regents exam. The same quiz was given to the students before and after completion of the activity; therefore, it is referred to as pre- and post-quiz [Supplementary Material Figure 2]. A survey following completion of the activity that consisted of five questions on a 1–10 scale was also conducted to assess both the students' and teacher's evaluation and opinion on the effectiveness and enjoyment of the activity [Supplementary Material Figure 3, 4]. The study was approved by the New York City Department of Education's Institutional Review Board (study numbered 1689).

Hypothesis

The ability of 3D prints to transform multiplex biological concepts into tactile physical objects allows the students to see and interact with the reality of their studies, helping them understand the purpose of the lesson and therefore remember the material better.

Participation and experimental design

Activities based on *Homoeostasis and Immunity* were presented to two classes of ninth grade New York State Regents Living Environment at the Urban Assembly Institute of Maths and Science for Young Women (UAI). The antibody modelling kit is beneficial for learning the topics of homoeostasis and immunity because it demonstrates how our antigens respond to antibodies and elicit an immune response against harmful viruses to maintain homoeostasis in the body. There were 15 students in the experimental class (n = 15), consisting of 100% female students with 64% African-American, 14% Hispanic, 12% Caucasian, 9% Asian, 2% other, and a teacher. There were 17 students in the control class (n = 17), consisting of the same demographics stated for the experimental group and a teacher. The students in both classes ranged from 14 to 15 years old. The day before the activity, both groups were given a 10-question pre-quiz that assessed their understanding of the material.

At the start of both classes, a 'BrainPOP' video was played to the students that briefly introduced the topics of homoeostasis and immunity through a short cartoon clip (BrainPOP 2017). All students in both the experimental and control group who participated in the design were able to watch the BrainPop video. This video explained the topics of homoeostasis and immunity by relating simple ideas such as shivering and sweating to more complex ideas such as how the immune system defends its body from invading viruses. They explained this as our body's way to keep us 'normal', and this general idea of maintaining normality prefaced the activities, which went more in depth as to how this normality is attained. The experimental group was then presented an antibody kit comprised of 3D prints. The kit contained models of antibodies IgG, IgA, and IgM, three of the most prevalent found in the human body. Although the students were not previously been exposed to specific examples of antibodies in previous lectures, they were given an explanation of their names and roles as they were freely interacting with the prints. This was kept at a basic level and focused solely on the antibody name, role, and basic structure. These antibodies were made from printed models of two adapter-like figures and one receptor-like figure that is forked (Figure 1). The adapter-like figures represented the base of the antibody, while the large receptor connected to the adapter, acting as the antibody's binding site.

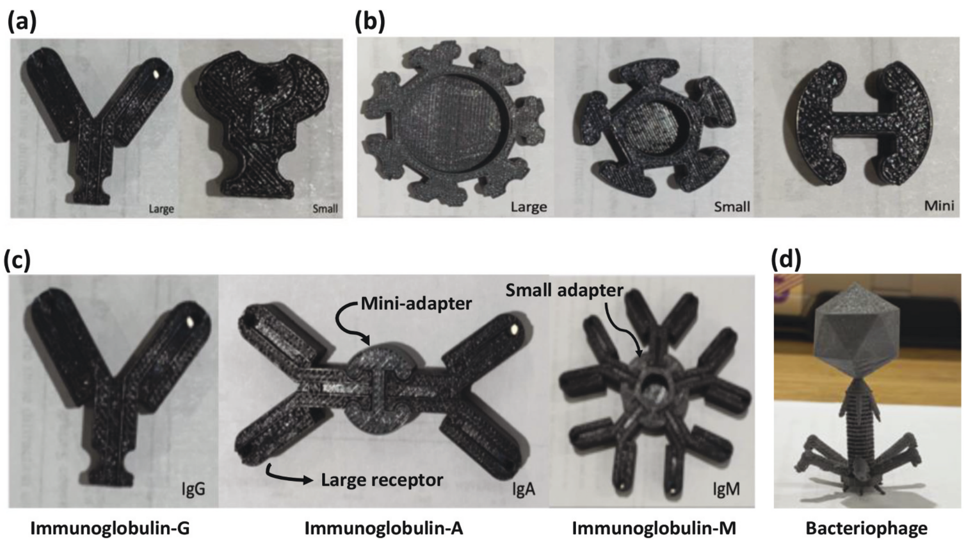

Figure 1. (a) Large and small receptors, resembling antibody binding sites and viral epitopes respectively. (b) Adapters of varying size: the small and mini adaptors form the base of IgM and IgA, respectively, while the large adapter forms the base of viruses. (c) Antibody models, made by adding large receptors onto mini and small adapters. (d) Bacteriophage T4.

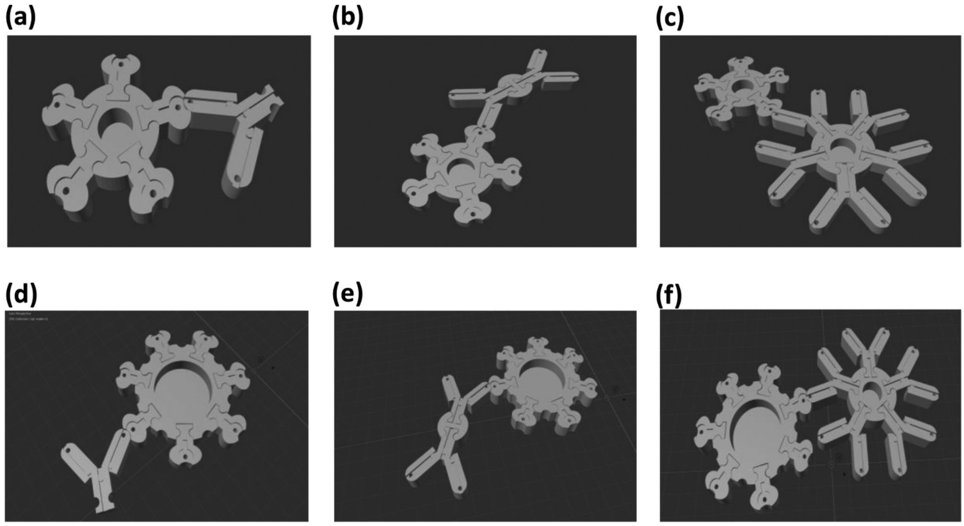

Figure 2. IgG (a, d), IgA (b, e) and IgM (c, f) binding to small and large viral antigen, respectively.

Antibody IgG is the smallest, comprised of just a single large receptor that pairs up with the virus it aims to degrade. Antibody IgA consists of a mini adapter and two large receptors, while antibody IgM consists of a small adapter and five large receptors (Figure 1(a, b)). IgA controls a variety of protective functions in the body, while IgM antibodies are the first to be made when a virus enters the body. These receptors pair up with the small receptors, or epitopes, on the viruses' antigens, which are formed by assembling a large adapter with small receptors (Figure 1(b, c)). This binding occurs through the use of magnets inserted into the 3D prints, enabling the students to depict an analogy of the antibodies moving towards the viruses and inducing their immune response through epitope binding. The kit also contained models of a type of virus called bacteriophage T4, another example of what the antibodies can degrade (Figure 1(d)).

Ultimaker Cura software was used to resemble the modelling of the antibody-antigen binding for all three antibodies and the two different viruses (Figure 2). To allow for a more accurate visualisation of the 3D prints, the Ultimaker Cura software was also used to measure the dimensions of the antibodies and virus models [Supplementary Material Figure 5].

The students were given freedom in handling the 3D models as three researchers walked around observing the groups. The researchers aided the students in connecting the pieces to represent the antigen-antibody binding. While the students were interacting with the antibody kit within a group of four to five, they were assigned an unstructured, participation-encouraged discussion on the role of each 3D print and how they interact with each other to keep the human body healthy. Although this discussion was open and encouraged for student participation, it was made sure that the same information was provided by the lecturers to both the experimental and control groups to allow for a fair assessment and comparison of the activities. The second part of the class was focused on different types of viruses. The purpose of this portion of the class was to demonstrate the variety and complexity of our bodies' invaders, and how these viruses can overtake our immune system leading to common illnesses. Students were given 3D prints of seven different types of viruses: the Dengue virus, Parvovirus B19, Human Papillomavirus 16, Hepatitis B, Phi X 174, West Nile, and Adenovirus (Figure 3) and a sheet including descriptions of each virus. They were then given time to observe and interact with the 3D prints, noting the similarities and differences between common viruses in a discussion-based setting similar to the previous topic, before taking the same quiz as at the start of class to test their understanding of the material covered.

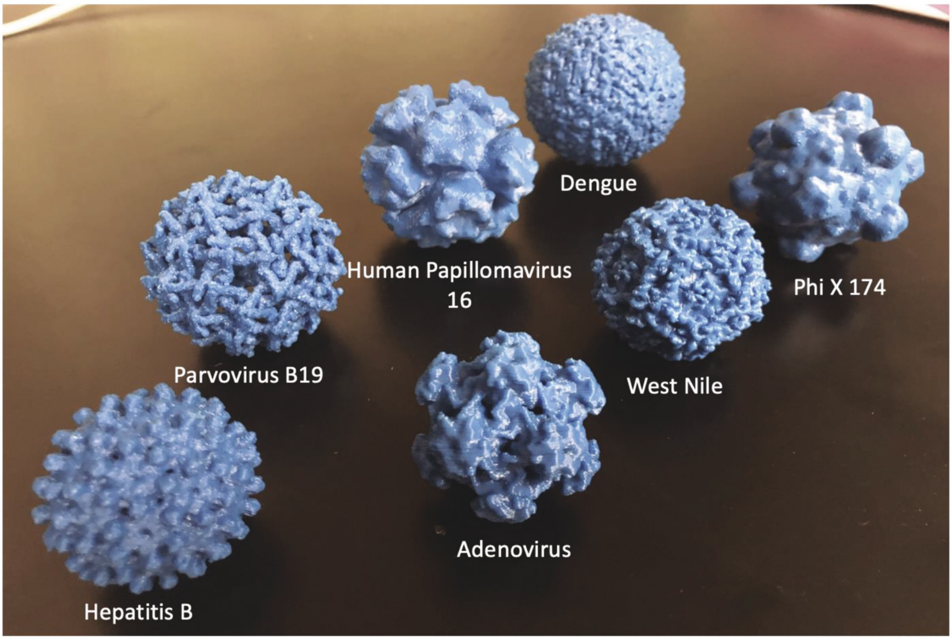

Figure 3. 3D prints of viral pathogens.

After watching the introduction video to homoeostasis and immunity, the control class was given a packet containing all of the information presented to the experimental group, however, instead of 3D prints the information was presented in a typed-out, 2D-image manner. The students were told to work together with their group to read the packet and answer questions in an accompanying worksheet. Similar to the experimental group, the control group was encouraged to discuss amongst their peers and researchers their thought process as they worked through the questions. Following the completion of the worksheet, the students individually took a post-quiz, the same one given to the experimental group [Supplementary Material Figure 2]. The class concluded with the completion of the same post-activity questionnaire. Although the format of the lessons was different, the content was kept consistent so that both, experimental and control groups had an equal opportunity to successfully complete the post-quiz. The control group had the opportunity to interact with the 3D prints the following day and gain the same tangible representation of the lesson that the experimental group received.

As stated previously, both activities contained all the information necessary to answer the questions in the quiz. The activity for the experimental group was significantly different than the lecture style the students were used to, while the activity for the control group was consistent with the standard lecture style. The teacher normally lectures the material to the students using the textbook provided by Pearson Education, Inc. After completion of both activities, the students and teacher completed a short post-activity questionnaire.

Results

Both the experimental and control groups took a quiz on the topics of homoeostasis and immunity before and after completion of their activities. The quiz consisted of 10 questions, and the mean scores of both the pre- and post-quizzes are indicated in Table 1. The scores of the experimental group were 3.5 ± 0.5 and 6.0 ± 0.7 for pre- and post-quiz, respectively.

Table 1. The average results of the students' quizzes before and after completion of the 3D-prints activity, with deviations representing the standard error of the mean.

	Pre-quiz score	Post-quiz score
Experimental Group	3.5 ± 0.5	6.0 ± 0.7
Control Group	4.3 ± 0.4	4.9 ± 0.5

Table 2. The average improvement results of the students' quizzes before and after completion of the 3D-prints activity, with deviations representing the standard error of the mean.

	Improvement in quiz score
Experimental Group	2.8 ± 1.4
Control Group	1.0 ± 0.7

The scores of the control group were 4.3 ± 0.4 and 4.9 ± 0.5 for pre- and post-quiz, respectively. The improvement in their understanding of the topics was assessed based on the results of pre- and post-quizzes. The improvement between the pre- and post-quizzes of the experimental group was 2.8 ± 1.4 while the improvement between the pre- and post-quizzes of the control group was 1.0 ± 0.6 (Table 2).

Upon completion of the activity and quizzes, the students were asked a 'Yes' or 'No' question to assess whether they liked the activity (Table 3). Both the experimental and control group stated they enjoyed their activities more than a traditional lecture class: 100% of the students in the experimental group answered yes to this claim, while 88% of students in the control group answered yes as well.

Both the students and teacher were then given a survey following completion of the activity to further gauge the overall impact of the activity. This survey also evaluated their opinions on the effectiveness of the 3D prints in helping them learn and understand the material. The survey consisted of five questions, all scaled on a Likert-like 1–10 scale with 10 being the greatest and 1 the lowest.

In the scaled questions for the student survey, the students' responses were evaluated on a Likert-like scale. When the students were asked if they enjoyed the lesson and activity (Table 4, Question 1), the average response of the experimental group was 7.9 ± 0.2, while

Table 3. The percentage of students who answered 'Yes' when asked if they enjoyed this 3D-print activity more than a traditional lecture class, with deviation representing the standard error. To calculate deviation, 1 was used for 'Yes' and 2 was used for 'No'.

Did you enjoy this learning style more than a traditional lecture class?	
Experimental group	**Control group**
100 ± 0	88.2 ± 0.2

Table 4. The average results of the students' answers to Questions 1 through 5 on survey concerning 3D print activity, with deviation representing the standard error of the mean.

	Experimental group	Control group
Question 1: On a scale of 1–10, how much did you enjoy today's lesson and activity?	7.9 ± 0.2	7.1 ± 0.3
Question 2: On a scale of 1–10, how well did you understand the topic before today?	6.2 ± 0.3	6.3 ± 0.2
Question 3: On a scale of 1–10, how well do you feel you know the topic at hand now?	7.0 ± 0.2	7.4 ± 0.2
Question 4: On a scale of 1–10, how much did the activity help you understand the material?	7.6 ± 0.2	6.5 ± 0.4
Question 5: On a scale of 1–10, how much do you normally enjoy a traditional lecture class?	5.1 ± 0.3	6.1 ± 0.3

the response of the control group was 7.1 ± 0.3. The results of a Kruskal–Wallis Analysis were insignificant (H = 1.0014, p = 0.31697); the mean survey results for Question 1 are not significantly different amongst the two groups. The latter portion of the survey then evaluates the students' opinions on the effectiveness of the activities in helping them learn the material. Both groups of students were asked how well they understood the topics of homoeostasis and immunity before they completed the activity (Table 4, Question 2). The average response of the experimental group was 6.2 ± 0.3, and the response of the control group was 6.3 ± 0.2. Based on the results of a Kruskal–Wallis Analysis (H = 0.0175, p = 0.89485), the mean survey results for Question 2 are shown to have a statistically insignificant difference amongst the two groups. Both responses are similar, as both classes were given the same amount of exposure to the topics before they completed the activities. The classes were in the process of completing the lesson on homoeostasis and immunity upon doing the activity, explaining the values being slightly higher than average. The students were then asked how well they feel they know the topics homoeostasis and immunity now (Table 4, Question 3). The result of this question for the experimental group was 7.0 ± 0.2, while that of the control group was 7.4 ± 0.2. The results of a Kruskal–Wallis Analysis (H = 0.212, p = 0.64519) show that the mean survey results for Question 3 are not significantly different when comparing the two groups. However, because these results were solely based on students' opinions of their understanding, this portion of the analysis was not as reliant as the pre- and post-quiz results. In the following question, the students were asked how much the activity helped them understand homoeostasis and immunity (Table 4, Question 4). The response of the experimental group was 7.6 ± 0.2, while the response of the control group was 6.5 ± 0.4. Following completion of a Kruskal–Wallis Analysis (H = 0.5993, p = 0.43885), the difference in mean survey results for Question 4 was found to be statistically insignificant between the two groups. For the final question, the students were asked was how much they normally enjoy a regular lecture class (Table 4, Question 5). The response of the experimental group was 5.1 ± 0.3, while the response of the control group was 6.1 ± 0.3. From the Kruskal–Wallis Analysis (H = 0.7544, p = 0.3851), there was a statistically insignificant difference between the groups' mean survey results for Question 5. As indicated by the teacher, the class was conducted in a teacher-centred discussion-based lecture.

A Shapiro Wilk test was performed on the pre- and post-quiz scores for both the experimental and control group to test for the normality of the results (Figure 4). The *p* values of the experimental pre- and post-quizzes were both >0.100, similarly to those of the control group. We, therefore, could not reject the hypothesis that our samples were normally distributed. The next test that was performed on the quiz results was a paired sample t-test, allowing us to measure the change in both groups' scores from pre- to post. A paired-sample t-test on the experimental group indicated that scores were significantly higher for the post-quiz (M = 6.0, SD = 2.5) than for the pre-quiz (M = 3.5, SD = 1.9), $t(14) = 2.99$, $p < .05$. The mean difference between the paired observations was significantly different for the experimental group, however not for the control. A paired t-test on the control group indicated that scores for the post-quiz (M = 4.9, SD = 2.1) were not significantly higher than the pre-quiz (M = 4.3, SD = 1.7), $t(14) = -1.17$, $p > .05$. The results of these analyses demonstrated the effectiveness of the intervention on increasing the material understanding compared to that of a normal lecture-style lesson.

The teacher involved with the study was also given the teacher's survey. The overall experience of the lesson and the 3D prints was rated as highly favourable, as the teacher stated that he thoroughly enjoyed the lesson. More specifically, when asked how much he felt the 3D prints activity improved his students' understanding of homoeostasis and immunity, the students' knowledge was first rated as a 5/10, which was scaled up to a 9/10. Lastly, the teacher stated that his favourite part of the lesson was the hands-on

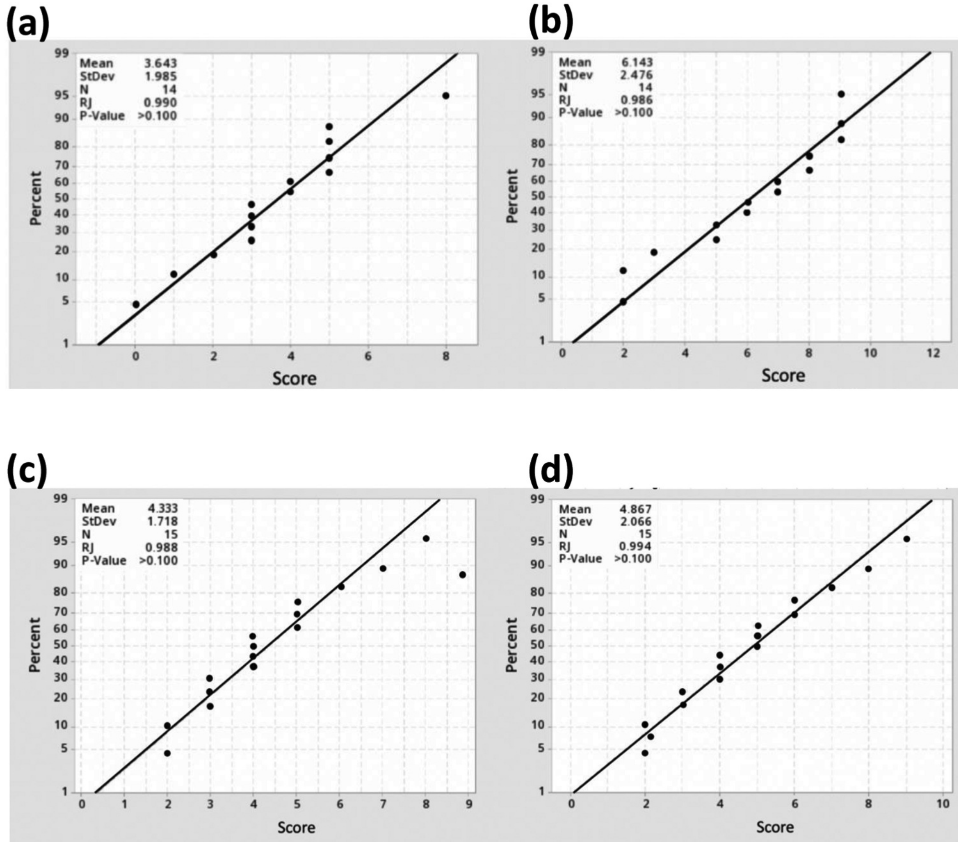

Figure 4. Normality graphs of the experimental and control group's (a, c) pre- and (b, d) post-quiz scores, respectively.

experience and the 3D representation of the viruses, believing they had a valuable impact on the students' education and enthusiasm in class. These results support previous research findings that 3D prints are capable of providing an appropriate supplement to biological curricula, previously shown by a statistically significant improvement in test scores associated with the use of 3D printed anatomical models (Lim et al. 2016).

Discussion

Using 3D prints in the Living Environment class helped teach the students biology topic of homoeostasis and immunity more effectively and realistically. From the results of the quiz, the students had a below-average understanding of the material before completion of the 3D prints activity. After the activity, however, their understanding increased to above average (Table 1). These results indicated significant improvements in the pre- and post-quizzes for the experimental group compared to the control group, demonstrating the effectiveness of the 3D prints.

By incorporating 3D prints with a more interactive lecture that encourages student participation, the results of the student survey indicated that the majority found that the prints helped them better learn and understand the concepts of homoeostasis and immunity as they more effectively translated the material in a real-world, tangible way. In a previous study on the learning preferences of a high school class, over two-thirds (68%) preferred active learning styles. Students from this referenced study found that they had increased confidence in the material after completing the activity along with a better analysis of the data, as was seen in the results from our studies as well (Wagner 2014).

Although there was greater improvement between pre- and post-quiz scores of the experimental group compared to that of the control, the student surveys do not strongly support these results. There is a difference between improved performance and improved attitude in student performance. This discrepancy between performance and attitude could be due to the lack of awareness surrounding the efficacy of the activity. Evidently, the students in the experimental group were not confident that the lesson helped them understand the topics at hand more deeply. Despite considering the activity more enjoyable than the traditional lecture class, the students most likely did not think it was as effective in educating. This may be due to the unfamiliarity of the hands-on, object-based learning presented to them (Atif, Benlamri, and Berri 2003). It will likely take more object-based learning lessons such as this one to allow the students to adjust and feel comfortable to reconcile their attitude in their own performance.

In addition to our studies, 3D prints are continuing to be used in high school biology classrooms, with concepts ranging from protein structure and folding, cellular constructs, enzyme action, and extensive molecular modelling (Davenport et al. 2017; Goodsell et al. 2015; Graham et al. 2017; Schelly et al. 2015). All cases have shown that the use of 3D prints has empowered student-driven engaged learning, provided a cost-efficient means of biology education, and seen notable improvements in student comprehension via a pre- and post-test assessment (Davenport et al. 2017; Goodsell et al. 2015; Graham et al. 2017; Schelly et al. 2015). Expanding on this, there have also been studies where learning was not statistically improved with a typical lecture-style lesson. A weak correlation was found between lecture attendance and class performance, and the amount of information retained was marginal (Horton, Wiederman, and Saint 2012; Michel, Cater Iii, and Varela 2009).

However, this student-centred object-based learning activity is not for everyone, as the connection between the prints and the material being covered can be weakened with less advanced, detailed models. This connection can also be strengthened by a more engaging and informative guided activity to supplement the 3D models. The models can also be more engaging for the students if they are more aesthetically pleasing, which can be improved upon with the implementation of more colour and functions into the prints.

The present study can further be advanced by developing new models and activities that are simpler yet more engaging. As the global pandemic continues, this study can be extended to include 3D models of coronaviruses that can cause severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS), and SARS-CoV-2. Since COVID-19 has affected all walks of life, we believe that students of all ages will be keen to learn the basis of interactions between viruses and antibodies. This will further help them understand the overall process of vaccine development and other treatment strategies that are actively being pursued to treat COVID-19.

Conclusion

From the positive responses in the classroom, it is clear that this lesson and activity had a positive impact on the students and teacher. The young women at the UAI greatly appreciated the activity as it helped them better understand the material, ultimately better preparing them for their New York Regents Exam. The teacher was delighted about students' participation in the activity and would recommend this 3D prints activity to reinforce the lecture material to other science teachers and well as implementing it into his curriculum. We will continue to collaborate with the teachers at the UAI to encourage the STEM field in exciting and interesting ways. Lastly, we will continue our research on the impact of technology and 3D prints in the classroom.

Availability of Data and Materials

All materials that were used to collect data can be found in the Supplementary Materials section.

Disclosure statement

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