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Gamified lessons support molecular genetics education of first year biology students during COVID-19 lockdown

Nicholas M. Andronicos, Terry J. Barnett, Raphael Roberts, Siew Chong, Lea Labeur, Sinead M. Henderson and Adrienne Burns
University of New England

This study compared the associated impact of gamified molecular genetics lessons on undergraduate student grades for pre-COVID-19 blended delivery and COVID-19 online only delivery of a first-year biology course. When the molecular genetics gamified lessons were used by on- and off-campus students to support their learning, most students had successful learning outcomes in either blended or online only learning environments. In contrast, students who chose not to use these lessons had significantly greater failure rates for both the molecular biology and the genetics short answer questions in the final invigilated exams. Importantly, there was noticeable gamified lesson fatigue observed by both on- and off-campus students and therefore when incorporating gamified lessons into courses, curriculum design needs to be carefully considered. In conclusion, the use of gamified lessons was associated with significantly reduced student failure rates for molecular genetics concepts studied in a university foundational biology course.

Keywords: biology, COVID-19, gamification, e-learning, blended, online, quantitative

Introduction

The learning success of undergraduate students studying STEM at university is usually dependent on didactic lectures as well as student laboratory experiences. In 2020, this was challenged with the advent of COVID-19 government-imposed travel and social gathering restrictions, forcing most Australian universities to deliver STEM courses in an online only environment (Crawford et al. 2020; Burns et al. 2021). This rapid transition to a fully online teaching environment required using e-learning technologies to deliver traditional STEM lessons asynchronously to students (Burns et al. 2021). The benefits of asynchronous delivery through e-learning resources have been shown to better support cognitive participation, improve reflective participation as well as deep learning, because students have more time to consider concepts (Garrison, 2016).

The structure/function of DNA (molecular biology) and Mendelian genetic inheritance are important, fundamental, concepts for undergraduate students to comprehend in biological science degrees (Cobb, 2018; Redfield, 2012). These conceptual topics are usually introduced to students together as molecular genetics in first year general biology courses at university (Cheesman et al., 2007). The order in which these topics are taught does not affect student learning success (Deutch, 2018). Didactic lectures and laboratory sessions are generally used to teach molecular genetics (Sheely, 2006; White, 2006). Recently, multimedia resources and auxiliary teaching methods have been used to augment these traditional teaching methods (Pelletreau et al., 2016; Liu & Taylor, 2013; Marshall, 2017; Mclean & Schuma, 2016; Yung and Primm, 2015; Hall et.al., 2014; DeBruyn, 2012; Altiparmak & Nakiboglutezer, 2009) and laboratory sessions (White & Bolker, 2008; cgslab.com; StarGenetics; DrosophiLab, FlyLab JS). Thus, gamified lessons were developed and deployed as the centrepiece resource to teach molecular genetics in blended and online only learning environments.

Gamification is the use of game design principles and mechanics to develop lessons that enhance student learning (Kapp et al., 2013; Loganathan, et al. 2019; Kalogiannakis et al., 2021). Game design principles such as visible status, freedom of choice, and freedom to fail with rapid feedback promote effective learning (Dicheva et al., 2015) and encourage student engagement in a low-risk environment (Bevins & Howard, 2018; Al-Azawi, et al., 2016), which improves the academic results of students (Bai et al., 2020). Therefore, it was hypothesized that the provision of students with a series of online, gamified molecular genetics lessons exclusively via an online learning environment would facilitate their learning outcomes comparable to students who studied molecular genetics using a blended learning approach consisting of face-to-face teaching and online lessons. Hence, the aims of this study were to:

1. Develop and deploy gamified lessons, designed to teach students foundational molecular genetics concepts in blended and online only learning environments.
2. Determine if the summative grades of students studying molecular genetics in a blended learning environment were comparable to students studying via an online only learning environment.

Methods

This study was approved (HE21-079) by the University of New England Human Research Ethics Committee.

Design and deployment of the molecular genetics gamified lessons

The gamified molecular biology interactive lesson: DNA and Protein Synthesis was built using Blender3D (Blender Foundation, USA), Tumult Hype (Tumult Inc, USA) and Adobe Captivate 2019 (Adobe, USA) as a HTML5 resource. Similarly, three gamified online genetics lessons (Meiosis and the Law of Segregation; Independent Assortment; and Pedigree Analysis) were also developed using Adobe Captivate. All lessons had a branched learning design that contained multiple learning modules (Table 1). These lessons included elements

Table 1. Gamified lesson design and learning interactions included in the molecular genetics' lessons.

Game Design Features	DNA & Protein Synthesis lesson	Segregation & Meiosis Lesson	Independent Assortment Lesson	Pedigree Analysis Lesson
Credits & Attributions	✓	✓	✓	✓
Table of Contents	✓	✓	✓	✓
Menu (Jump Page)	✓	✓	✓	✓
Number of Modules	3	2	2	2
Learning Objectives	✓	✓	✓	✓
Module Navigation Tabs	✓	✓	✓	✓
Next Button on Success	✓	✓	✓	✓
Progress Counter	✓	✓	✓	✓
Lesson Length	66 Pages	49 Pages	28 Pages	49 Pages
Learning Interactions & Static Resources	**DNA & Protein Synthesis lesson**	**Segregation & Meiosis Lesson**	**Independent Assortment Lesson**	**Pedigree Analysis Lesson**
Static Info Pages (%)	14 (21%)	9 (18%)	5 (18%)	10 (20%)
Drag and Drop Activities	6	6	1	2
Text Entry Box Activities	9	22	28	42
Click Box Activities	0	8	28	38
On-demand Popups (% / Page)	8 (12%)	4 (8%)	4 (14%)	9 (18%)
Rollover Help Info (% / Page)	0 (0%)	3 (6%)	3 (11%)	7 (14%)
Feedback (% / activity Page)	40 (77%)	41 (103%)	62 (270%)	99 (254%)
Drop Down Activities	3	0	0	3
Embedded Videos	5	3	2	3
Fill in the blank question	0	1	0	0
Multiple Choice Questions	12	11	4	7
Searchable Glossary	×	✓	✓	✓
Total Learning Activities	43	59	71	109

such as avatars, activity-related components and sound tracks (Jayalath & Esichaikul, 2020). Each module was designed to be completed within approximately 20 minutes (i.e., the estimated average attention span of adult learners (Middendorf & Kalish, 1996)). Drop-down table-of-contents and ubiquitous module tabs facilitated fine and gross lesson navigation, respectively by students. Lessons also contained a variety of leaning activities such as multiple-choice questions, drag-and-drop interactions, text entry boxes and drop-down selection activities. Non-assessable marks were associated with each lesson so that students could map their learning success (i.e., a

total of 34 multiple choice questions across all lessons). Sound tracks were also added to the lessons to enhance engagement. Importantly, the percentage of static information pages was kept to about 20% in each lesson. Most lessons had a high density of immediate feedback for the learning activities to assist students with comprehension and lesson completion.

First year biology course

On- and off-campus students enrolled in the first-year biology course received the same teaching material delivered via the Moodle LMS platform. The number of students enrolled into the first-year biology courses in 2019 and 2020 were 418 and 433, respectively. In 2019, prior to COVID-19, the first-year biology course at the University of New England was delivered as a blended learning course consisting of: didactic lectures and laboratory sessions for Module 1: Life, Cells and Microbiology; Module 2: Genetics and Molecular Biology; Module 3: Energy and Metabolism (biochemistry); and Module 4: Animal Structure, Function and Behaviour. On-campus students attended three 1-hour lectures per week and one 4-hour lab session. By contrast, off-campus students watched the weekly recorded on-campus lectures and their laboratory sessions were delivered as a four-day intensive school. However, during the 2020 Government-imposed lockdown restrictions, lectures and laboratory sessions were delivered in an online only mode because on-campus students were unable to attend classes in person. Off-campus students were also unable to attend the campus for intensive schools during 2020. The 2019 (pre-COVID-19) and 2020 (COVID-19 lockdown) students had comparable final invigilated exam questions to assess the molecular genetics component of the course (Figures 1 and 2).

Molecular Biology Exam Question Example

You are given the sequence of a DNA sense strand below:

5'GGAATTCATGGCATTTAGAGTTTAGAAGAATTCC 3'

a) Copy the above DNA sequence as part of your answer and write the complementary sequence of the strand underneath it, showing the 3' and 5' ends. (2 marks)

b) Write the mRNA sequence coded by the above DNA strand showing the 3' and 5' ends. (2 marks)

c) Identify and label the start and stop codons on the mRNA sequence. (2 marks)

d) Use the codon usage table below to translate the mRNA of the gene into the correct amino acid sequence of the protein? (4 marks)

(Note: Students were given a codon usage table to use in the exam).

e) The DNA sequence from part (a) contains a gene that we need to clone into bacteria so we can express large quantities of this recombinant protein. Step 1 of cloning this gene into bacteria involves cutting the DNA with the restriction enzyme EcoR1, which has the recognition site GAATTC. Find and underline the GAATTC recognition site(s) in this DNA sequence. (2 marks)

f) Briefly describe the other steps required to clone this gene into bacteria for protein expression. (3 marks)

Figure 1. An example of the molecular biology short answer question of the final invigilated exam.

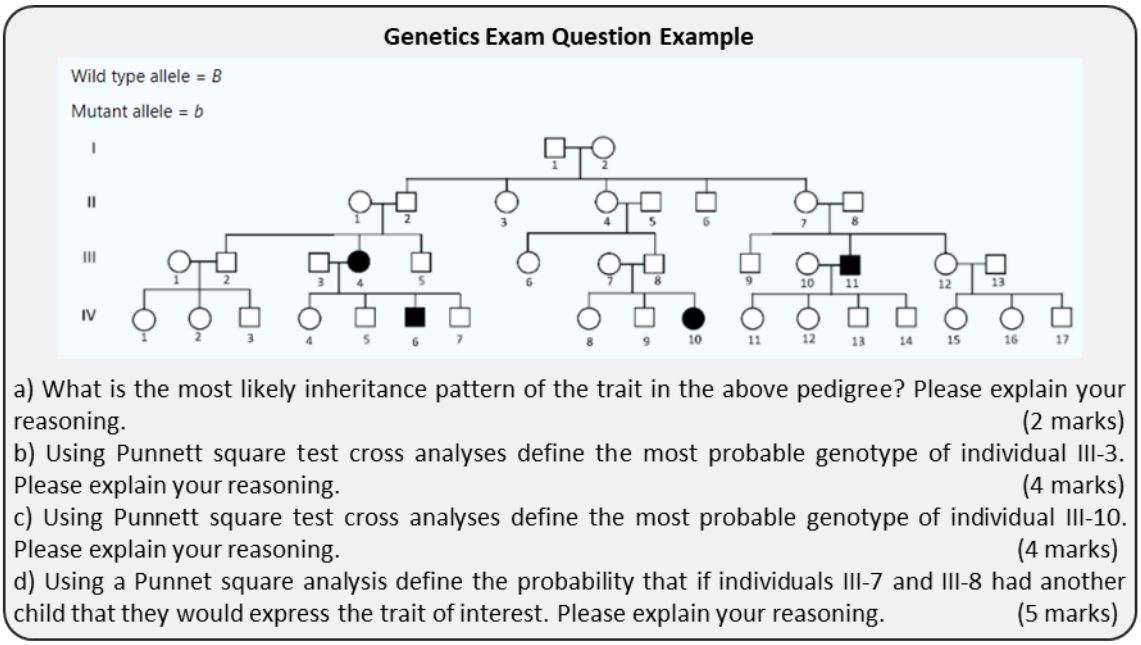
Results

Gamified lesson use.

The usage of the gamified lessons by each student cohort was determined from the lesson SCORM data reported by the Moodle LMS. For the gamified DNA lesson there were no significant differences in lesson usage between cohorts or across years (Figure 3). The maximum engagement of students with the online DNA lesson was 63%. Therefore, because there were no significant differences between on- and off-campus student cohorts relative to enrolments and the DNA online lesson usage across years, student learning outcomes were directly comparable for these cohorts. Since three gamified lessons were developed to teach the genetics content of this course, contrasts between students who used all three genetics lessons compared to student that did not use any of these genetics gamified lessons to support their learning were made. During 2019 (pre-COVID-19), when the biology course was delivered in a blended learning mode, there was a significant ($\chi^2 > 16.949$; $p < 0.00021$)

decline in the number of off-campus students who accessed lessons 2 and 3 compared to lesson 1 to augment their study of genetics. Moreover, significantly ($p < 0.05$) fewer on-campus students used the gamified genetics

Figure 2. An example of the genetics short answer question of the final invigilated exam.



lessons to support their learning compared to the off-campus student usage of genetics lesson 1. These data may indicate that there was online lesson fatigue demonstrated by students studying molecular genetics with blended teaching. Similarly, during 2020, when first year biology was delivered exclusively online, a small, but significantly ($\chi^2 > 11.806$; $p < 0.0027$) greater number of off-campus students used the first genetics lesson compared to those who used lessons 2 and 3. Some gamified lesson use fatigue trend was also apparent in the on-campus student cohort.

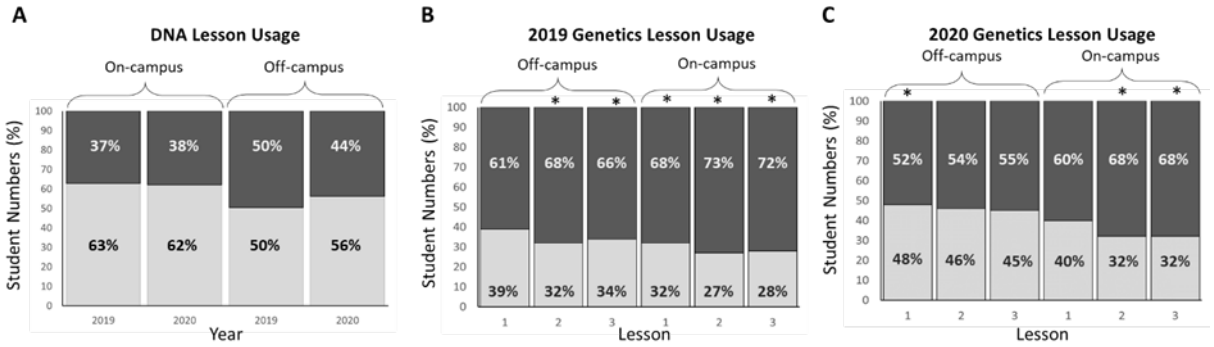


Figure 3. Student lesson usage data for 2019 and 2020 for first year biology. (A) The percentages of on- and off-campus students that used the DNA lesson once (▫) or that did not use the DNA lesson (■) throughout the teaching periods in 2019 or 2020. (B) The percentages of on- and off-campus students that used all three genetics lessons once (▫) or students who did not use any of the genetics lessons (■) 2019 or (C) 2020.

Student learning outcomes associated with gamified lesson use.

Not all students enrolled into the first-year biology course voluntarily accessed these gamified lessons to support their molecular genetics learning, Therefore, it was hypothesised that the student outcomes on the molecular genetics final exam questions would improve if they had used these lessons compared to students who chose not use these lessons. In 2019 (pre-COVID-19), when a blended delivery mode was used, both on- and off-campus students who used the online DNA lesson during the teaching period achieved a significantly ($p < 0.004$) higher

average grade for the molecular biology question on their final invigilated exam compared to students who did not use the online DNA lesson (Figure 4). However, in 2020, during the COVID-19 lockdown, on-campus students who accessed the DNA lesson had a significantly ($p = 1.30\times10^{-6}$) higher average grade on the final DNA exam question than students who did not use this lesson, whereas there was no difference in the average grade on the final molecular short answer exam question between students that did or did not use this lesson. The average grade achieved by the 2019 on-campus student cohort who used all three genetics lessons were significantly ($p = 0.0023$) higher compared to on-campus students who chose not to use these lessons, whereas in 2020 there were no differences in these cohorts for the average grade achieved on the genetics short answer question for the final exam. Thus, the deployment of a single gamified lesson may have proven more effective at enhancing the learning outcome of students than the deployment of multiple lessons to teach a topic.

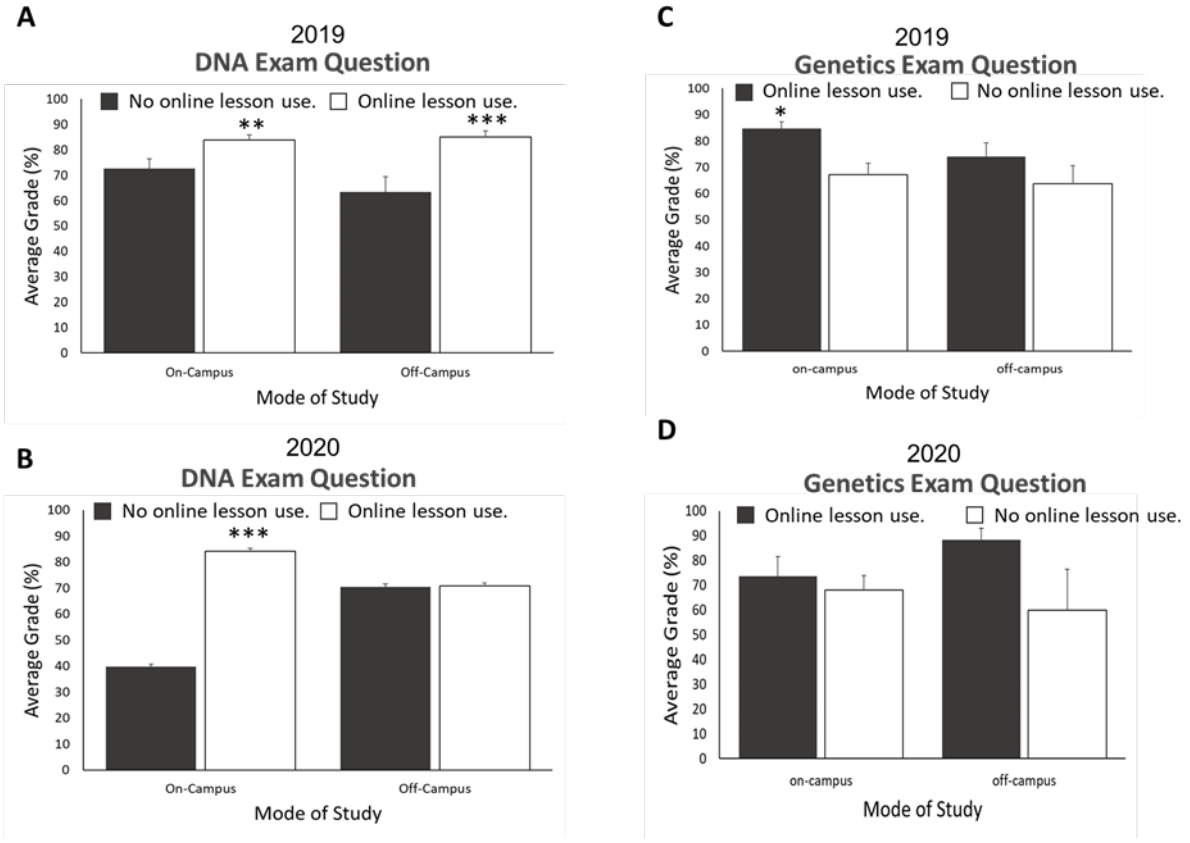


Figure 4. Average grades of on- and off-campus students who used or did not use the gamified lessons. (A and B) The percentage of average grades of on- and off-campus students who either used (☐) or did not use (■) the online DNA lesson and who answered the molecular biology short answer question in the 2019 and 2020 invigilated final exams. (C and D) The percentage of average grades of on- and off-campus students who either used (☐) or did not use (■) all three genetics lessons and who answered the genetics short answer question in the 2019 and 2020 invigilated final exams. * $p < 0.05$; ** $p < 0.01$, *** $p < 1\times10^{-5}$.

In 2019 and 2020, 93% and 77%, respectively of on-campus student who accessed the DNA lesson once, passed the molecular biology exam question (Figure 5). Similarly, in 2019 and 2020, 93% and 79%, respectively of off-campus students who used the DNA lesson once, passed the molecular biology short answer question on the final exam. Thus, significantly more students who used the DNA lesson in 2019 (pre-COVID-19), blended delivery and 2020 (COVID-19) online only delivery modes passed the final molecular biology short answer exam questions. For the genetics section of the course, since three lessons were developed, the learning outcomes of only those students who used all three gamified lessons were considered in the analysis. In 2019 and 2020, 96% and 72%, respectively of on-campus students who used all of the genetics lessons at least once, passed the short answer genetics question on the final exam. Similarly, for both 2019 and 2020, 88% of off-campus students who used these lessons passed the genetics short answer question on the final exam. Across all student cohorts and years, a minority of students who used these online lessons failed the molecular genetics short answer questions on the final exam with the exception of the 2020 molecular biology question. Thus, these data suggested that usage of the online gamified lessons by students to support their learning of molecular

genetics was associated with successfully passing the short answer molecular genetics questions on the final invigilated exams, independent of the mode of delivery of the course material.

Since it was apparent that student engagement with the gamified lessons was associated with an increase in the pass rate for both on- and off-campus students independent of blended or exclusively online delivery, the effect of learning success was further quantified relative to grade stratifications achieved by students who used these gamified lessons compared to student who did not use these lessons (Figure 6). Stratification of grades from the

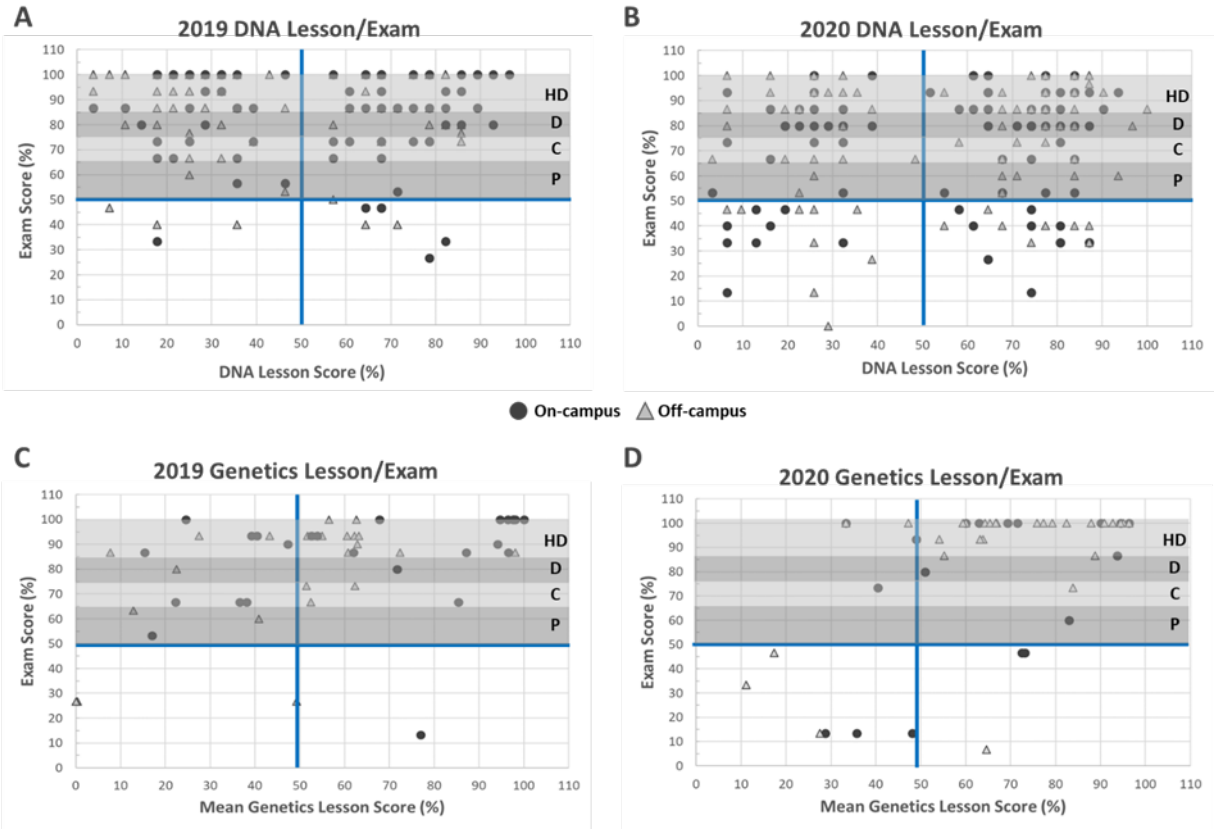


Figure 5. Quadrant plots demonstrating the molecular genetics short answer question exam scores against gamified lesson scores for (A and B) the DNA synthesis lesson and (C and D) the genetics lessons for on-campus (●) and off-campus students (▲). Note for the DNA lesson data is presented for students who used the lesson once, whereas for the genetics lessons data is presented for students who used all three lessons to augment their learning. High distinction (HD; 100-85%), Distinction (D; 84-75%), Credit (C; 74-65%), Pass (P; 64-50%) and Fail (F; 49-0%).

molecular question on the 2019 invigilated final exam demonstrated that there were significant increases in the number of both on- ($\chi^2 = 8.455$; $p = 0.0146$) and off-campus ($\chi^2 = 11.268$; $p = 0.0036$) students that failed the molecular biology invigilated exam question and who did not access the online DNA lesson during the teaching period. Also, in 2019 there was a significant ($p = 0.0083$) increase in the number of off-campus students who achieved a passing grade for the molecular biology short answer exam question who accessed the DNA lesson compared to students who did not use this lesson. Similarly, in 2020 ($\chi^2 = 9.9054$; $p = 0.0071$), significantly more on-campus students who did not use the gamified DNA lesson failed the molecular biology question on the final invigilated exam compared to students who used the lesson, whereas, there were no differences in grade stratification observed for the 2020 on- or off-campus cohorts. Similar trends were apparent for the students who answered the genetics short answer question on the final invigilated exams. Collectively, these exam data suggested that use of molecular genetics lessons by students was associated with better exam pass rates, but did not significantly improve the proportion of students achieving the higher grades on the molecular biology or genetics short answer questions in the final exam.

Discussion

This study describes the development, deployment and student outcomes of gamified lessons designed to teach students foundational concepts in molecular biology and Mendelian genetics. These data supported the hypothesis that the use of gamified lessons by students, was associated with successful learning outcomes, as determined by

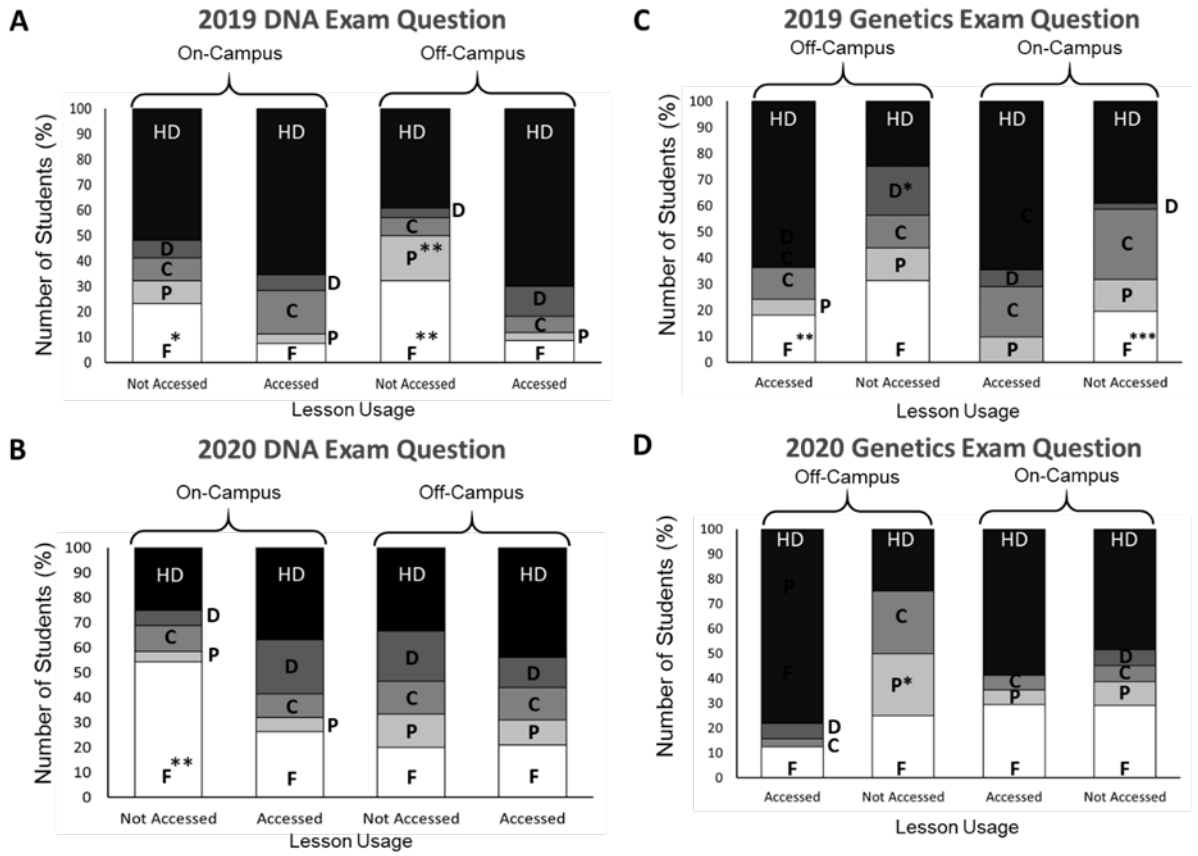


Figure 6. The grade distributions of on- and off-campus students who used the gamified lessons compared to students who did not use these lessons to support their learning. (A and C) Percentage grade distribution of on- and off-campus students who either used or did not use the online DNA lesson and who answered the molecular biology short answer question in the 2019 and 2020 invigilated final exams. (B and D) Percentage grade distribution of on- and off-campus students who either accessed or did not access all three genetics online lessons and who answered the genetics short answer question in the 2019 and 2020 invigilated final exams. High distinction (■; HD; 100-85%), Distinction (■; D; 84-75%), Credit (■; C; 74-65%), Pass (■; P; 64-50%) and Fail (□; F; 49-0%). * p < 0.05; ** p < 0.01; *** p < 0.005.

invigilated exam success, compared to students who did not use these lessons when studying molecular genetics via blended or online learning modes. Design of effective gamified lessons should contain intuitive but unobtrusive navigation features thereby allowing the student to concentrate on the lesson content game mechanics (Moshirnia & Israel 2010), thus potentially enhancing their learning experience (Pilke, 2004). In these lessons, both coarse and fine navigation controls were included to facilitate maximum navigation flexibility, thereby enhancing the usability of these lessons for *prima facie* learning as well as revision by students. A gamification meta-analysis study of STEM subjects demonstrates that these types of resources significantly increased STEM student learning outcomes (Huang et.al., 2020). Pleasingly, this same meta-analysis study identified that the game components included in our lessons (Table 1) have benchmarked our gamified lessons at world's best practice, since these components are recognised as important game elements that facilitate STEM learnings by students.

Importantly, student progression through gamified lessons must be balanced against overloading students with too much information, which although essential for the learning outcomes of the lesson may impede students from completing these lessons. Features that enhance student progression, include the provision of immediate

feedback (Alabbasi, 2018; Doney, 2019; Sepehr & Head, 2013) and hints, designed to support informed student choices during their learning activities. These features also promoted increased concept comprehension (Kanthan & Senger 2011). However, feedback considerations must be balanced against the temptation of designers to include too much information via the excessive use of pop-ups in gamified lessons, which detracts from lesson flow (Moshirnia & Israel 2010). Thus, on-demand popups were included in these lessons to support student who desired extra support for their comprehension. The provision of on-demand pop-up access did not detract from lesson game flow and enabled students who did not desire this level of enhanced support to maintain their progression rate through the lesson. Similarly, a virtual tutor avatar was used to give feedback to students as well as provide them with on-demand hints to assist students with their learning, thereby minimising the use of informational popup windows in the lesson. Avatars also enhance the quality of learner engagement by guiding and retaining student attention without textual overload. However, student feedback indicated that excessive narration by the avatar was distracting, thus narration was strategic and terse.

A diversity of learning activities in gamified lessons is also recommended (Huang et.al., 2020, Bonora et al., 2019; Filippou et al., 2018) to achieve the learning objectives (Bicen & Kocakoyun, 2018; Loos and Crosby, 2017; Meinel & Schweiger, 2016) and is associated with improved student performance. Thus, the gamified molecular genetics lessons contained assorted learning activities which were expected to increase the recall of concepts by students (Fotaris et al., 2016) and improve student attention (Alabbasi, 2018).

The gamified lessons were deployed as a hub and spoke resource, designed to be the primary learning resources of the molecular genetics module in the first-year biology course. As the principal learning resources, the students were encouraged to supplement the gamified lessons with lectures delivered by the teaching staff. As such, these lessons were the centrepiece of the 2019 pre-COVID-19 blended delivery of the molecular genetics' module the biology 1 course. Most of the on- and off-campus students who used these lessons passed the corresponding short answer question in the final invigilated exam. Consequently, the use of these lessons by the students was associated with fewer failures suggesting these lessons may have augmented student comprehension of molecular genetics. This trend continued during the 2020 COVID-19 lockdown when the molecular genetics content was only delivered online, suggesting that using gamified molecular genetics lessons supported remote student learning.

However, if gamified lessons are used in isolation to promote deep understanding of highly conceptual topics by students there was no increase in the performance of students (Aji & Napitupulu, 2018; Orhan et al., 2019). Therefore, teachers should provide direct learning support to students when using these types of lessons. For this reason, the molecular genetics lessons were deployed as the primary learning resources that were supplemented with additional learning material as required, and especially frequent teaching staff communications with students (Burns et al., 2021).

Limitations, Conclusions and Recommendations

A perceived limitation in the design of this study was the omission of student learning outcomes from mandatory student pre- and post-lesson testing metrics. However, by employing voluntary student lesson use as the independent variable, lesson use fatigue could be ascertained, which has curriculum design implications. In conclusion, when the gamified lessons were used by on- and off-campus students as part of their learning strategy, most students had successful learning outcomes in either blended or online only learning environments. In contrast, students who chose not to use these lessons had significantly greater failure rates for the molecular genetics short answer questions in the final invigilated exam. Recommendations from this study include:

- That the use of well-designed, gamified lessons, which teach foundational STEM concepts significantly enhanced student learning outcomes in blended and online-only learning environments, and that to develop these lessons, it would be advantageous for institutions to provide learning design support and/or academic teaching relief.
- Some gamified lesson fatigue was also observed and therefore, the overuse of these resources should be avoided and importantly, the gamified lessons did not replace lecturer-centred student support.
- Future research may include performance tracking students in scaffolded degrees where the concepts taught by gamified lessons in foundation courses are required knowledge for higher level course.

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