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Development of Gamified, Interactive, Low-Cost, Flexible Virtual Microbiology Labs That Promote Higher-Order Thinking during Pandemic Instruction†

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The COVID-19 pandemic radically and without warning changed the laboratory learning environment for students and instructors. Students were faced with having to be receptive to new learning methods; instructors scrambled to devise innovative ways of providing a realistic lab experience for students. The demand for creative online teaching strategies and the expansion of gamified training platforms created an opportunity for the development of new and interactive lab experiences. Current online labs offer some elements of a "real" lab experience, but a system that incorporates all the tools needed to create a realistic, immersive lab environment has yet to be developed. This study examines using different gamification elements implemented in a PowerPoint-based platform. There was no cost associated with the virtual lab and it could be easily downloaded, increasing accessibility. In true gaming style, a student could "play" without restriction, without the limitations that accompany wet labs. Students were challenged with various scenarios throughout the lab, making choices and receiving feedback through the process. These features positively impacted student outcomes and improved engagement, as expressed in end-of-course evaluations. The implementation also stressed the need for further development of embedded assessments, competitive and interactive opportunities for students, and access to detailed learning analytics for instructors.

INTRODUCTION

The Internet generation of students is expected to possess a multivaried toolset to be successful. Beyond digital literacy, today's students should be adept in complex thinking and creativity (1). Learner-centered and active-learning approaches to education have been shown to be highly effective in achieving many of these goals (2, 3) by engaging students in learning activities and assessments that involve discussion, reflection, and collaborations among groups of students. Models including problem-based learning, flipped classrooms, and independent learning in conjunction with collaborative learning have been developed to achieve these goals (4), especially in the biomedical sciences. Researchers also suggest that complementing these engaging activities with technology is essential to enhance the current pedagogies (5), including using educational games (6). However, the current pandemic has forced institutions to resort to emergency remote teaching and shift teaching to an online modality. Several factors must be considered with e-learning: accessibility in remote and rural areas, affordability, flexibility in instruction, learning pedagogy delivery, promotion of lifelong learning, and an educational policy that provides equitable and quality access to learning materials (7).

With the COVID-19 pandemic, the need for virtual instructional resources became an instant reality. In the time span of days, in-person classes and labs were halted, and instructors were tasked with moving all educational delivery into the virtual environment. BIOL2516K Microbiology with Laboratory for Health Science (Georgia Gwinnett College, the target course in this discussion for which virtual lab modules were developed) typically includes both a lecture and laboratory component. Online instruction meant either sacrificing the on-ground lab component or replicating laboratory activities in a virtual space in accordance with the established curriculum guidelines for Microbiology for Nursing and Allied Health courses (8, 9). Several virtual lab experiences that both demonstrate techniques and challenge users to think critically regarding the validity of their outcomes were developed. The techniques addressed including aseptic transfer, smear preparation, simple staining, capsule stain, quadrant streak isolation, and Gram staining, the latter of which is provided here as an example. Scheckler (10) argues that virtual labs are not a new phenomenon, stressing the advantages of repeatability, high

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degree of realism, accessibility, and an increased flexibility in collaboration over time and location. Virtual teaching has revolutionized remote learning and expanded access to educational resources (11). The lineage of virtual labs traces back to educational technologies such as projectors, radio, and television, all once lauded as improvements on the instruction taking place in a face-to-face setting (12).

Lab activities are essential in the student learning process, allowing students to develop skills and proficiency through manipulation of tools, observation of outcomes, and interpretation of the proficiency of their technique performance—skills that are unattainable in a solely lecture-based setting and that provide scaffolding to deepen understanding. Through engagement and properly structured activities, students apply previous knowledge and strengthen and further expand their mastery of those skills (13).

While prior research indicates students' preference strongly gravitates to face-to-face (F2F) over virtual instruction (14), the laboratory experience has undergone a substantial structural evolution in the last several decades. As technology has advanced, virtual instruction platforms have transformed teaching and learning. Studies have shown that virtual simulations had positive impacts on students' retention of skills and broadened their comprehension of fundamental concepts (15). Data have shown that students perform similarly in introductory biology virtual labs and wet labs, scoring slightly higher in the virtual labs where at-home test-kits were employed, based on analysis of covariance of lab scores comparing F2F lab students with virtual lab students (16). Students also perceive the accessibility and usefulness of online labs as more convenient and just as effective as wet labs (17). Virtual labs are safe, more cost effective, and portable, leading to an increased student preference for this mode of instructional delivery (16, 17).

However, virtual labs do not always encompass all the components an instructor wishes to teach in an authentic virtual simulation. Many limit user interactivity or engagement by offering rigid lockstep instructions, with no mechanism for user exploration, inquiry, adaptive learning, or engagement. While success has been shown with virtual lab demonstrations of procedures to prepare students for biology (18), it could be argued that this pedagogy is procedural in nature, not engaging students in higher-order thinking skills, active learning, or student reflection (19). Few virtual labs offer a real-life "feel," and many emphasize little in terms of lab safety or lack a lab safety component altogether (13). Scheckler (10) argues that "the quality of the experience from virtual labs does not have the immediate impact" that working with actual lab specimens and tools provides. Demonstration-style virtual labs are suitable for technique instruction but lack components that enable development of logic and critical thinking skills; they also limit student inquisitiveness. Traditional hands-on labs involve high costs associated with equipment, space, and maintenance staff (18), even if smaller, physically distanced F2F sections are offered.

Gamification, the use of game design elements in non-gaming contexts (20, 21), has become a popular tool used by a wide array of educators during the last decade and targets students primarily at the university level (22). The subject with the most educational gamification is predictably computer science (39%), with math, communication, medicine/biology/psychology, and languages representing other large proportions of the subject coverage at 10%, 12%, 10%, and 8% respectively (22).

Gamified educational experiences can enhance learning, increase engagement, and encourage positive behavior and motivation (23, 24). Hamari *et al.* (25) reviewed two dozen studies and reported most yielded positive results in terms of the relationship between gamification and learners' engagement. Seaborn and Fels (26) reviewed 32 studies on the use of digital gamification elements in teaching. Of these 32 studies, 20 yielded positive results, making connections between gamification and increased levels of motivation and engagement, while the remaining 12 showed no correlation.

Gamification of learning offers new tools to boost knowledge acquisition (27–29), enhance students' understanding of the material (30, 31), improve the development of critical reasoning skill (32, 33), increase motivation (34, 35), raise engagement with the subject material (36–39), provide a real world application (40, 41), and improve social skills (42, 43). These outcomes are especially important in preparing STEM students as well as crucial for all students who are receiving online instruction. A wide variety of employed game elements are represented in the literature, including competition, badges, leaderboards, points and levels (29, 31, 40, 43–45).

On the other hand, gamification must consider and properly address the front end of the design process in order to produce its desired effects. Gamification can produce higher extrinsic levels of motivation; however, this is temporary unless coupled with other factors from self-determination theory (SDT), including autonomy, competence, and relatedness (46). Creating a gamified learning experience requires that educators design for long-term positive effect—mainly, an increased intrinsic motivation so that the long-term effects of gamification can be properly measured (23). Gamification requires an understanding of SDT, motivation, engagement, fun, emotions, and player types. Focusing on gamification beyond points and levels is crucial; otherwise superficial game design can damage existing interest/engagement with learners (47).

In biological and medical sciences, existing gamified lab instruction can be divided into three formats: (i) electronic games, where the learner participates in a competitive activity with some set of preset rules; (ii) mobile applications, where the learner uses software on a handheld device to assist in training, and (iii) virtual simulations, in which the learner interacts with real-life scenarios for education and assessment (48). Bonde *et al.* (40) examined the effect of gamified lab-based simulations in biotechnology students, finding an increase in learning outcomes and student motiva-

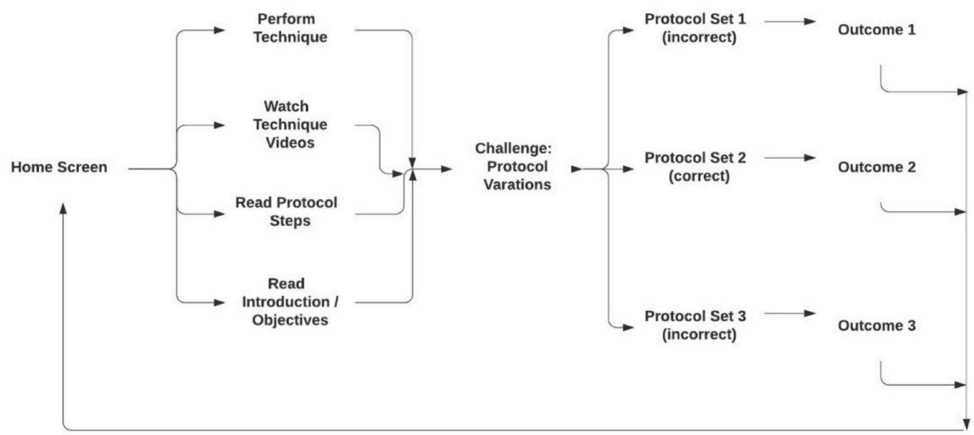

FIGURE 1. Design schematic displaying all the pathways based on student progression through the module. The module design allows for multiple experiences.

tion. Geelan *et al.* (41) developed an interactive educational tool (Body Central) to help first-year undergraduates develop bioscience fundamentals, finding that students were more engaged with content, enjoyed the experience, and achieved significantly improved learning. Fleischmann and Ariel (49) used gamification to aid understanding and troubleshooting of microscopic process via an interactive web-based learning tool to visualize enzyme-linked immunosorbent assays; 90% of the student feedback reported a positive and enjoyable learning experience. These gamified virtual lab experiences also incorporate real-world application, are offered in an asynchronous or synchronous teaching mode, and remain accessible to all learners.

DISCUSSION

Design

This study examined using virtual, gamified, and multimodal lab simulations in a way that would combine the positive aspects of traditional wet labs with a suitable platform for enhanced student engagement (Fig. 1; functional sample module in Appendix 1). Lab simulations began by providing core content about the module and progressed to implementation of gamification components to increase student interest, engagement, and motivation. According to Geelan *et al.* (41), positive influences on student learning involve combining the presentation of information with game-based, active-learning elements. A study by Freeman *et al.* (3) found that students are more successful, and more inspired to be successful, when the learning environment is highly engaging compared with traditional lecture-based methods. According to Langendahl *et al.* (50), the activeness of teacher and students is an ebb and flow process wherein, at one point, the teacher might be in an active role and in the next instance, the student is in the active role; in this dynamic the students and teacher are co-creators of meaningful teaching and learning environments (50). The design of the gamified virtual lab modules kept this in consideration.

The lab simulations are comprised of a series of interactive PowerPoint slides that have been modeled after a Choose Your Own Adventure (CYOA)–style game in order to promote inquiry and engage the students. This format is very popular in the current video game market (e.g., Red Dead Redemption and Cyberpunk 2077). Much like these video games, our modules allow users to have total control over the consequences of their actions, though in a much shorter story arc than the aforementioned games. Even when students are not yet proficient, they have a sense of connection to the decisions they make. The simulations allow them to acquire the required knowledge, skills, and attitudes in a controlled space, where experimentation poses no risk to themselves or to others. If the desired outcome is not achieved, an added benefit is that the module

TABLE 1.
Minimum system requirements for virtual lab module use.

Computer Type	Laptop or Desktop
Processor	Intel Core i3 processor or higher (most computers in the past 5 to 8 years)
Operating System	Mac OS X 10.13 or later (latest version recommended); Windows 7 or later (Windows 10 recommended)
Browser	Latest version of Chrome, Firefox, or Microsoft Edge; latest version of Safari on Mac (for browsing course content)
Microsoft PowerPoint	PowerPoint 2016 (part of MS Office 2016) or later; PowerPoint mobile available (https://www.microsoft.com/en-us/store/p/powerpoint-mobile/9wzdncrfjb5q) or on the web (https://office.live.com/start/PowerPoint.aspx)
RAM	4GB or higher
Connectivity	Ethernet or Wireless connection; cable modem or DSL

can be replayed, with alternative choices and outcomes that promote learning from one's original choices.

The modules are PowerPoint presentation files that contain embedded video in MP4 format (.mp4), which is natively supported on all operating systems and does not require any additional applications or codecs to play the content (see Table 1 for minimum system requirements). These files have also been optimized for size, placing a lower burden on students with limited connectivity. Saved as PowerPoint Presentation files (.ppsx), these modules contain navigation within, so that students can play the simulation and explore different outcomes based on the choices they make in an offline mode.

The following tools were used for the dissemination of the core content. A more detailed description of the specific design process and expectations for how students were instructed to use the virtual modules (Appendix 2), as well as sample classroom discussion questions, an online quiz, and practical exam questions (Appendix 3) are also included.

- Overview of learning objectives: provided an overall comprehensive context highlighting expected results.
- A detailed introduction: provided the context on mechanics of the technique, including visual representations of expected results in each step. The introduction also included a discussion on the importance of performing steps in the correct order.
- A complete directive: provided written, step-by-step details for technique performance in the protocol. Users were also provided opportunities to explore potential consequences for procedural missteps.
- A video tutorial: demonstrated the technique from the perspective of the student. To strengthen the connection between written instructions and the visualization of those instructions, a verbal narration of the steps was simultaneously provided.

These lab simulations encompass several gamification elements. Visual elements, including original technique videos and actual photographs of outcomes, were included to promote a sense of community and interaction with the instructor. Students feel more engaged when they can interact with the professor and the lab environment (51). The technique videos offer the advantage of a first-person perspective for the student. The student will find it more appealing and feel more immersed in the simulation experience if, visually, it looks as though the student is performing the experiments.

Once students have progressed through the information-acquisition phases of the lab, they are faced with challenges and choices, modeling many CYOA game apps and books that are popular today. Each lab proposes a series of challenges to the student. Challenges motivate students and entice them to keep playing (50). For example, the student may be asked to perform the technique but may have several protocol pathways from which to make their choice to proceed. Rather than expecting a mere description of results to be meaningful to students, by encompassing opportunities for students to explore and further investigate outcomes that model errors in technique, these modules develop critical reasoning skills. As students proceed through the lab simulation, they are presented with graphics highlighting the expected results, erroneous or accurate depending on the chosen path.

During this time of exploration and decision-making, the student may choose to revisit parts of the lab by simply clicking the correct "button" for the corresponding part of the lab they want to revisit. This offers the student a chance to assess their progression and readiness for the challenge and personalizes their development, as needed. In traditional labs, students may encounter limitations in learning, such as time restrictions or a lack of material accessibility or personalized instruction (52). Enabling students to learn at their own pace and tailor the learning to their needs allows them to alleviate such constraints that otherwise detract from a meaningful learning experience (53).

When a choice has been made, the student clicks a button to perform their protocol or experiment of choice and is given informative feedback immediately in terms of a visual photograph of the outcome and a confirmation that the protocol was either performed correctly or incorrectly. This feedback includes a rationale for why the choice is correct or why it is incorrect and provides a simple explanation of how the error impacted the outcome, if required. This strategy allows the student to see immediate consequences of their choices and what, if anything, they need to improve (50). Students can return to the challenge and make a different choice as well as return to other parts of the simulation for review. This "replay" permits students to play as many times as they desire without worrying about real-life consequences (50) or incurring higher fees for consumable materials.

Strengths of the lab simulations

A series of elements were employed in the labs to increase student engagement and motivation. The students incurred no cost in accessing the labs. Virtual lab simulations such as these are a useful tool for institutions that are unable or unwilling to use at-home lab kits. Students were able to access and download the no-cost virtual labs to their computers at their convenience. Great care was taken to compress the video tutorials in both video and audio sampling rates to keep file sizes as small as possible while maintaining high quality. These downloadable labs allow for a more equitable dissemination of information and provide students, even those with physical disabilities who may have otherwise had a less inclusive lab experience, the chance to be fully included in the learning experience. The ability to download rather than stream the labs circumvented the problem of students' lack of Internet access and increased the portability of their learning experiences, allowing for a more robust review mechanism than a traditional F2F lab, where access to lab content is restricted. Here, labs can be accessed anytime and anyplace, increasing overall access. Students appreciated the flexibility of having a platform that offered unlimited attempts to learn the content (17).

The gamified components of the lab simulations motivated students to engage and manage their own learning experience while employing higher-order thinking skills that paralleled the F2F experience as much as possible (Table 2). Students were faced with challenges during the lab and asked to make choices. With each choice, they immediately received feedback on the outcome. This feature allowed students to monitor their progress and determine whether retraining was necessary (48). This risk-free environment inspired students to accept increased responsibility for their experience.

Shortcomings of the lab simulations

The lab simulation offered many elements that improve student learning and student engagement and brought up aspects that negatively impact student outcomes and impede instructor monitoring of student learning. Despite attempts to design a lab simulation with equitable accessibility for students, this system requires initial Internet access for downloading as well as capable playback software (Table 1). For a subset of the student population, these are obstacles to enjoying the full benefits of this design. Currently, the lab simulation is paired with online discussions and quizzes (Appendix 2) provided by the instructor after completion of the virtual lab. However, embedded assessments would allow the students to monitor their progression through the lab and self-assess, helping them resolve any misconceptions or knowledge deficiencies during the module rather than at the end. Moreover, embedded quizzes would also offer the instructor access to valuable learning analytics by providing progression reports, timely student feedback capabilities, and end-of-game reports (48). The continuous monitoring of student learning and swift instructor responses would enrich student engagement and motivation and improve the likelihood of continued "play" by the student (53).

Gamification provides collaborative elements to an online experience, However, the current design does not provide this element. The opportunity to work together offers students the sense of working as a team toward a common goal (48). The development of a competition and leaderboard system with the lab simulation would provide a platform for building a sense of community among the "players" in addition to offering incentives for students to improve their performance (41). With this tool, students can reflect on individual performances as well as the performance of the learning community, thus developing individual and collective decision-making skills and critical thinking.

Future directions

Although the simulations used in the course sections surveyed in this study lack embedded quizzes, future revisions will incorporate self-assessments, providing students an opportunity to measure their progress throughout the module/lab, consistent with best practices of online teaching established by Quality Matters (http://www.qualitymatters.org).

In the spirit of continuous quality improvement, the next iteration will contain several instruments to measure effectiveness of the modules. Specifically, the following will be deployed for data collection and assessment:

- Critical incident questionnaires: Questionnaire (54) to capture student reflection
- Preassessments: Student surveys prior to experiencing modules, capturing perceptions of the material and the format

TABLE 2.
Comparison of higher-order thinking skills assessed in F2F labs vs. virtual labs employed in this study.

Higher-Order Thinking Skills	F2F Labs	Virtual Labs
Identifies proper technique	✓	✓
Emphasizes understanding of technique	✓	✓
Promotes application of technique	✓	✓
Evaluates performance of hands-on skills	✓	
Analyzes proper protocol choice/utilization	✓	✓
Evaluates outcomes of correct/incorrect protocols[a]	✓	✓
Creates an individualized experience		✓

[a] Limited in F2F, occurs only when students produce errors during their performance; the errors are already built in to the virtual experience.

- Post-surveys: Student surveys after experiencing modules, capturing perceptions of the material and the format
- Mid-term check-in: Just-in-time feedback about user experience, coupled with focus groups, provides rich qualitative and quantitative data to use for course improvement plans

SUPPLEMENTAL MATERIALS

Appendix 1: PowerPoint presentation module for Gram stain process
Appendix 2: Virtual lab design process and construction
Appendix 3: Expectations of students and sample questions

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