Building bacterial knowledge: Games as teaching aides for higher-order thinking skills

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Building Bacterial Knowledge: Games as Teaching Aides for Higher-Order Thinking Skills

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Abstract: Bacteria Builder is a videogame designed to teach student nurses about bacterial form and function within the context of a university fundamental science module. It challenges players to design and build bacteria with appropriate structures for surviving in different environments. This paper describes two studies undertaken to explore the most effective way to use the game as part of teaching on the module. 152 student nurses took part in the first evaluation, which used a control group to compare learning gains for a) only the game b) only the lecture and c) the game plus a reflective activity. All three conditions demonstrated improvements over the control, but there were no significant differences in learning gains between the experimental conditions. In a second evaluation, 124 student nurses took part in a study which compared the lecture on its own to the lecture and game together. Learning gains were found to be over 50% higher in the lecture and game condition, and subsequent analysis showed that the nurses who had played the game made greater improvements in questions designed to test higher-order thinking skills.

The design and motivation behind the Bacteria Builder game is described and the results of these studies are discussed with respect to the role of teaching in maximising the effectiveness of game-based learning. Correlations between interaction data for different parts of the game are explored with respect to learning outcomes, and implications for the design of future studies are discussed.

Keywords: Game-Based Learning, Teaching Aide, Microbiology, Higher-Order Thinking Skills

1. Introduction

This paper explores the effect of using a learning game called "Bacteria Builder" to help undergraduate nurses gain a more in depth understanding of the form and function of bacteria. The game was created specifically to teach this content as part of a university fundamental science module for first year trainee nurses. Practical teaching constraints meant that the bacterial structure topic had been taught in a traditional, large lecture format with limited potential for practical exploration of the subject matter. As such, engagement with the topic was observed to be low, and students rarely grasped the complexity of the range of bacterial morphologies and how they affect bacterial survival in different environments. Motivation and engagement is often considered critical to the learning process (Lepper and Malone 1987) and it is difficult for nurses to transfer and apply their knowledge to a clinical setting if they cannot engage with traditional teaching methods. Game-based learning has been widely applied as an engaging way to teach science topics as diverse as genetics, relativity, tectonics, neuroscience and nutrition (Li and Tsai 2013) and gaming approaches have already been used successfully with nurses to develop critical thinking skills (Rowell and Spielvogle 1996). There is also a natural opportunity for interactive gaming systems to incorporate deductive reasoning and hypothesis testing (Dondlinger 2007) and investigate complex systems (Squire 2002) in ways that are much harder with traditional teaching materials alone.

Smart phones have become a ubiquitous technology, and the availability of powerful mobile devices makes mobile-learning an attractive platform for educational games. Notably, the size of the mobile games market in 2017 demonstrated the highest rate of increase for any market relating to educational games (Takahashi 2013) and is predicted to continue increasing in the future (Adkins 2016). The availability and portability of smart phones makes them ideal as a platform for teaching resources, as users require less training and are less likely to feel intimidated by their own devices. This familiarity can help to make a potentially overwhelming, complex topic such as microbiology seem more approachable, while avoiding any potential stigma associated with mainstream gaming technologies (Klopfer 2008). Bacteria Builder was therefore conceived as mobile-based educational game to be used alongside the existing lectures. It was hoped that a game would provide an engaging platform which would give student nurses an opportunity to make use of their knowledge to create their own internalised model which furthers their understanding and application of the learning content.

2. Building Bacteria

It is essential for nurses understand the threat that bacteria pose in a healthcare environment so that they can reduce the spread of infection and appreciate the limitations of finite resources such as antibiotics. However, poor engagement in the fundamentals of microbiology can result in a superficial understanding of the subject matter and leave nurses ill-equipped to apply their knowledge to new situations within a healthcare setting. Game-based learning is often associated with higher-order thinking skills and constructivist approaches to learning (Charsky and Mims 2008). Higher-order thinking is defined as the group of skills that occupy the upper end of Bloom's Taxonomy which include, from lower to higher order: knowledge, comprehension, application, analysis, synthesis and evaluation. The final three skills fall within the domain of higher-order thinking skills and are considered to be particularly valuable for deep learning (Bloom, et al. 1956).

A constructivist approach suggests that learning occurs as part of an active process of constructing ideas and relationships in the learner's mind rather than simply being exposed to information (Piaget, 2001). Learner's further their knowledge and understanding through their own observations and experiences gained through experimentation. Applying an experimental approach to learning about bacteria in the real world could carry the risk of dangerous outcomes such as contamination or infection, especially in a healthcare setting. A game however, provides a safe 'sandbox' (Gee 2003) environment for experimenting with bacteria, as well as the ability to accelerate natural processes so that they can be more easily visualised and experiments undertaken.

It was this rationale that led to the design approach for Bacteria Builder. Rather than destroying bacteria it was decided to put the player on the side of the bacteria, providing the opportunity to create optimal bacterial structures to survive in different environments in line with the *synthesis*-level thinking skill. This approach was also considered to be compatible with a pre-dominantly female audience of nursing students. Research suggests that games which are fast-paced or violent are less popular with female players (Cassell and Jenkins 2000, Kafai 1996) and constructivist approaches to mainstream games such as The Sims (Sihvonen 2009) and Minecraft (Anderson, et al. 2017) have previously proved popular with female audiences.

3. Microbiology

Microbiology is the branch of biology that specialises in the study of microorganisms and it is studied as a core topic as part of accredited nursing degrees in the UK. To practice as a registered nurse within the UK the degree curriculum must cover five essential skills, one of which is "infection prevention and control" (Nursing & Midwifery Council, 2015). A basic understanding of bacterial structure and function can help nurses understand how bacteria grow, survive, and aid them in significantly reducing the risk of infections and controlling the spread of such infections through to their patients and the healthcare environment.

To support this aim, Bacteria Builder incorporates a range of core bacterial features which allow them to adapt to their environment, the most important of which are their structures, as bacterial adaptations are determined by the type of components possessed by bacteria:

- Flagellum – A rotating tail which provides the ability for bacteria to move through liquid environments.
- Efflux Pump – A biological pump which enables the extraction of antibiotics from inside the cell, making them resistant to specific antibiotics.
- Fimbriae – Tiny hairs which allow the bacteria to stick to their environment.
- Capsule – A thick protective layer which prevents the bacteria from drying out and allows them to stick to their environment.

It is important to understand the compatibility of different components alongside their role in bacterial function. For example, a bacterium cannot possess a flagellum and a capsule, as a flagellum would not be able to protrude and rotate through the thick capsule layer. Bacterium would also either be motile, or adhere to a surface, both lifestyles cannot occur simultaneously. These relationships help to reinforce a deeper understanding of how the composition of bacteria are specialised for different environments.

Bacteria only possess the minimum number of structures to allow them to survive within an environment, excess structures would be disadvantageous to the bacteria as valuable resources would be wasted making them meaning the bacteria would be outcompeted in the environment and perish. To embed an appreciation for this basic evolutionary principle, each structure had a cost associated with it; flagellum and capsule had a cost of 3, fimbriae a cost of 2 and efflux pumps a cost of 1. The higher the total cost a build, the fewer bacteria entered the environment.

In addition the user can also determine the bacterial shape:

- Coccus (spherical) – Their smaller relative surface area slows the rate of desiccation, but this also reduces the rate of multiplication due to slower nutrient intake. In addition, cocci bacteria are almost exclusively non-motile, so in Bacteria Builder flagella are not permitted with this shape.
- Rod (round-ended cylinders) – Their large surface area increases nutrient intake, leading to improved rates of division, but it also increases the rate of desiccation.
- Vibrio (curved rods) – Commonly possesses a polar flagellum to enable it to move faster than other bacteria; in the context of the game vibrio with flagella have improved speed over rods with flagella.

While these generalisations are not true for every bacteria of each shape, it was necessary to give each shape specific strengths in the context of the game. This provides the user with a reason to use one shape over another and also gives some insight into the general properties commonly associated with these shapes.

4. Game Design

4.1 Design Goals

The overall design goal for Bacteria Builder was to create a game which allowed players to experiment with bacterial shape and structure and explore the suitability of their bacterial designs to survival in contrasting environments. This can be broken down into a hierarchy of learning goals according to Bloom's Taxonomy for the cognitive domain (Bloom, et al. 1956):

- *Remember* common bacterial shapes and structures.
- *Comprehend* the implications of these shapes and structures on bacterial function.
- *Apply* an understanding of bacterial function to predict the utility of structures to different environments.
- *Analyse* the relationship between shape, compatibility of structures and associated energy costs.
- *Synthesize* optimal bacterial structures to survive in different environments.

These requirements needed to be designed into an accessible mobile game which could be used along-side a lecture without being too obtrusive or disruptive to the teaching environment.

4.2 Design Overview

There are many different formal approaches to game design, ranging from motivational taxonomies (Malone and Lepper 1987) to conceptual "lenses" (Schell 2014), but here we will consider Bacteria Builder in terms of the Mechanics, Dynamics and Aesthetics (or MDA) Framework (Hunicke, LeBlanc and Zubek 2004):

Aesthetics

It was decided that the player's aesthetic experience of the game would be embodied in the fantasy context of a scientific lab. There would be no specific narrative story behind the game, just an open challenge to try and design bacteria to survive in different kinds of environments. This would be a discovery-based learning process in which the player was required to conduct experiments and observe the results. In terms of the MDA framework this incorporates *fantasy*, *challenge* and *discovery* as the key aesthetic goals which determine the player's perspective on the game, and we felt that this would produce an appropriately 'casual' gaming experience for the intended audience.

Dynamics

This aesthetic experience would be provided through two dynamic systems: the first allowing the player to build bacteria with different shapes and structures, and the second allowing them to observe the rapidly accelerated growth of the bacteria within a pre-set environment (the "simulation"). The *fantasy* of the scientific lab context would be embedded within the graphical design (lab coats, microscopes *etc.*) and the *challenge* would be reinforced with a star-based reward system. *Discovery* would be intrinsically built into the game by the replay loop of experimenting, adapting and retrying in order to achieve the optimal solution with the maximum number of bacteria surviving (indicated by a three star rating).

Mechanics

The core mechanics underlying the first dynamic system would consist of selecting bacterial shapes and adding and removing components from them. Feedback would be provided to the player about the "cost" of complex components as an indication of the initial number of bacteria that would be released into the environment. The core mechanics of the simulation would be largely passive: observing the bacteria multiply and die according to their suitability to the environment. Although the player's interactions with bacteria (touching them) would not affect the outcome at this stage, they would reveal additional information about what was happening and provide clues as to how to improve outcomes for successive experiments.

4.3. Game Structure

The final structure of the Bacteria Builder game is shown in Figure 1. The player is introduced with a welcome message followed by the option to select an environment for their bacteria. They are then presented with a small amount of information regarding the conditions their bacteria will face. Next, they select the shape of their bacteria, with each shape having a different effect on survival within each environment. The player is then taken to the build stage, where they can add components to specialise the bacteria, information is provided on how a component affects the bacteria at the bottom of the screen as each component is selected (Fig. 2). This allows the user to make decisions on what is useful based on the chosen environment. The player then has the option to name their bacteria before it is placed within the simulation.

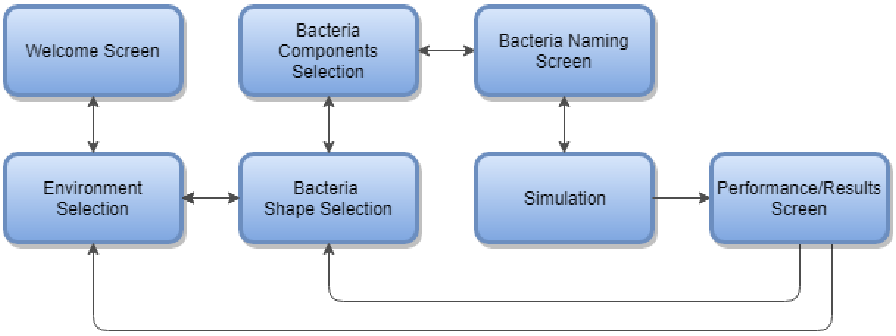

Figure 1: A Flow diagram showing the screen sequence of Bacteria Builder.

When the simulation begins (Fig. 2), a small number of the player's bacteria are placed within the environment and the timer starts. Timing is arbitrary, and has no "real-world" scale, but is suggestive of time passing at a faster than normal speed. The bacteria begin to multiply (if they can), and for certain events that relate to the environment to unfold. The environments and events are as follows:

Soil:
- Some of the other bacteria present within the soil produce antibiotics.
- Rain initially provides moisture but stops mid-way through leaving the sun to dry out the environment.

Work Surface:
- Remains dry and baron of nutrition throughout, preventing bacteria from multiplying at all.

Inner Ear:
- Waves of earwax periodically push bacteria out of the ear.
- A wave of antibiotics can sweep over the bacteria if the ear is irritated enough by high numbers of bacteria.

Bloodstream:
- Waves of antibiotics periodically sweep over the bacteria.
- White blood cells can seek out and engulf bacteria.

Once the simulation ends, the player is presented with a results screen. Here they are shown a message congratulating them on their success and/or providing hints for improving the performance of their bacteria. They are also given a score out of 3 stars depending on how appropriate their choice of bacterial structures was for this environment. Scores (stars) are saved and displayed on the level selection screen below the image of the environment they relate to, so the player can track their progress.

Figure 2: The Bacteria Structure Selection Screen (left) and Simulation (right) from the Bacteria Builder game.

4.4 Iterative Design

The design of Bacteria Builder followed an iterative approach in which the game was regularly trialled with users and adapted according to the feedback provided. Four formative testing and feedback sessions were conducted in schools with children of different ages ranging from 11 to 17 years old. Three more sessions were with students and staff from the university and the game was also shown at the university's annual science fair, where more feedback on the game was collected.

5. Method

5.1. Aims and Hypotheses

Two studies were undertaken with different cohorts of BSc Nursing students to evaluate the effectiveness of the Bacteria Builder game. Practical teaching constraints meant it was not possible to examine all of the research questions we were interested in using a single study. Study 1 was designed to compare students' learning from the game and the lecture independently of each other. Study 2 was designed to compare the benefits of using Bacteria Builder alongside a lecture, in comparison to the lecture alone. Study 2 also examined the depth of learning in terms of higher order thinking skills.

Based on the literature and design described above, several hypotheses were formed:

A. Both the game and lecture would independently provide learning gains as compared to a control.
B. The game combined with the lecture would result in higher learning gains than the lecture alone.
C. The game would provide a greater improvement in questions that address higher order thinking skills as compared with the lecture alone.
D. The level of interaction with the game will predict learning outcomes.

Hypothesis A was the focus of study 1, and hypotheses B, C and D were explored in study 2.

5.2. Participants

The participants for the studies were two separate cohorts of first year undergraduate, BSc Nursing students at the researchers' institution. The first cohort consisted of 170 nurses in total and 152 participated in Study 1. The gender split in the first study was 88% female and 12% male. The second cohort consisted of 381 nurses in total and 124 took part in Study 2. The gender split in study 2 was 90% female and 10% male. The students in Study 1 where slightly younger, with 69.9% of students being under 21 compare to 54.7% in Study 2.

5.3. Measures

A multiple-choice test was developed to measure participant's microbiological knowledge before and after the interventions. These contained 20 questions delivered in a different random order between the pre and post-tests. Each question was designed to fit a specific level of Bloom's Taxonomy, with 5 questions addressing *knowledge* and 3 questions each for *comprehension*, *application*, *analysis*, *synthesis* and *evaluation*. An example of each type of question is provided in Table 1 below. The same test was used in studies one and two.

In addition to the pre and post-test results, detailed analytics were gathered from the game to explore the player's interactions with the game and any effect on learning outcomes:

i. The time spent within each simulation attempt.
ii. The number of stars gained for each simulation attempt (out of 3).
iii. The bacterial shape and makeup for each simulation attempt.
iv. The total number of button presses on the build screen (includes shape and component selection).
v. The total amount of time spent on the build screen.

All the analytics data was recorded along with the participant's ID number allowing the players' test scores to be matched to their corresponding in-game analytics.

Table 1: Examples of questions relating to each skill within Blooms Taxonomy (Bloom, et al. 1956). The multiple-choice answer options are listed a) to d), with the correct answer in bold.

Knowledge	Cocci bacterium are? **a) Spherical** b) Rods c) Comma-shaped d) Cuboidal
Comprehension	Which structure is the most costly to a bacterium? a) Efflux Pumps b) Pilli c) Fimbriae **d) Flagella**
Application	Which structural component is most advantageous to bacteria on a dry surface? a) Efflux Pumps b) Flagella **c) Capsule** d) Fimbriae
Analysis	What shape is the bacterium staphylococcus aureus? a) Comma shaped b) Rod shaped **c) Spherical** d) Rectangular
Synthesis	Which combination of components will be optimum for a microorganism living upon the palm of a hand? **a) Capsule** b) Fimbriae **c) Efflux Pump** d) Flagella
Evaluation	Which component is necessary for a microorganism living upon a toilet seat to survive? **a) Capsule** b) Fimbriae c) Efflux Pump d) Flagella

5.4. Procedure

Both studies were run as part of normal two-hour sessions scheduled as part of the nurses' fundamental science module and delivered in large lecture theatres. Each study involved two or more experimental groups, and assignment was achieved using colour-coded booklets handed out at random at the start of each lecture. Each booklet was labelled with a unique ID code (e.g. BLUE-7) and included a blank set of pre and post-tests. In both studies, each participant was given the same time to answer the pre and post-tests and were asked to guess answers if they didn't know them. Silence was required throughout the pre and post-test phases. In both studies mobile tablet devices were provided for students who were assigned to play the game.

Table 2: The practical schedule for study 1. The number of minutes for each phase is indicated at the top of each column (120 in total). Pre and post-tests are shown in yellow and intervention activities in green.

Group	10	15	15	15	15	15	20	15	Students
Control	Introduction	Pre-Test	Practical			Post-test	Lecture	Anatomy Test	37
Lecture Only	Introduction	Pre-Test	Practical			Anatomy Test	Lecture	Post-test	38
Game Only	Introduction	Pre-Test	Practical		Game	Post-test	Lecture	Anatomy Test	38
Game+ Reflection	Introduction	Pre-Test	Game	Reflection Activity	Practical	Post-test	Lecture	Anatomy Test	39

Study 1

Participants were randomly assigned to four colour groups, each with different schedules (Table 2). The study consisted of several stages for all groups: an introduction; the pre-test (completed before any intervention), an arbitrary practical activity (unrelated to bacterial function), an anatomy test (unrelated to bacterial function), a post-test, and a lecture covering bacterial form and function. However, the order in which students experienced these was contrived to provide: i) a control group who completed the post-test with no intervention; ii) a group whose intervention consisted only of the lecture; iii) a group whose intervention consisted of just the game; and iv) a group whose intervention consisted of the game and a reflection session to discuss the games' intended learning outcomes after finishing playing it.

Debriefing from study 1 suggested that the time allowed for the introduction and lecture was not quite long enough, while the time allowed for the pre and post-tests was too long (with students getting restless after 10 minutes). The lengths of these phases were adjusted accordingly in study 2.

Study 2

Participants were separated into two colour groups (Table 3). Non-participants were treated as part of the Lecture group, but their pre and post-tests were discarded. This study consisted of similar stages to study 1, but in a slightly different order: the pre-test (completed before any intervention); an introduction; a lecture covering bacterial form and function; an arbitrary practical activity (unrelated to bacterial function); and a post-test. The order in which students experienced these was contrived to provide: i) a group whose intervention consisted only of the lecture.; ii) a group whose intervention consisted of the lecture followed by the game.

Table 3: The practical schedule for study 2. The number of minutes for each phase is indicated at the top of each column (115 in total). Pre and post-tests are shown in yellow and intervention activities in green.

Group	10	15	30	25	25	10	Students
Lecture	Pre-test	Introduction	Lecture	Practical		Post-test	95
Lecture+ Game	Pre-test	Introduction	Lecture	Practical	Game	Post-test	29

6. Results

The results from Study 1 (Fig. 3A) were used to compare pre and post-test scores for the four experimental groups: *control*, *lecture only*, *game only* and *game plus reflection*. The results from Study 2 (Fig. 3B) were used to compare pre and post-test scores for *lecture only* and *lecture plus game* groups.

Study 1 demonstrated statically significant learning gains for both the lecture and game groups (with or without a reflection session) as compared to the control. All interventions had a similar effect, increasing test score by approximately 2 points. There was no statically significant difference between the learning gains produced by the three intervention groups in Study 1 (ANOVA, data not shown).

Study 2 went on to investigate the use of Bacteria Builder as a tool to complement teaching and used the same methods to compare the effect of a lecture to a lecture and the game, both interventions showed a statistically significant learning gains. Interestingly the effect of combining the lecture and the game in a blended learning approach was additive, with the lecture leading to a 4.8 ± 3.4 point increase compared to the to lecture and game which showed a 7.3 ± 4.0 point increase ($p \leq 0.001$ student *t*-test).

Participants in study 1 had a higher pre-test score compared to Study 2, further analysis of the demographics of these cohorts of students shown those in Study 1 had much higher entry qualifications than those in study 2 (data not shown). Interestingly, the lecture in both studies lead to a post-test score of ~6.5, pointing towards an upper limit to the impact the lecture has on learning.

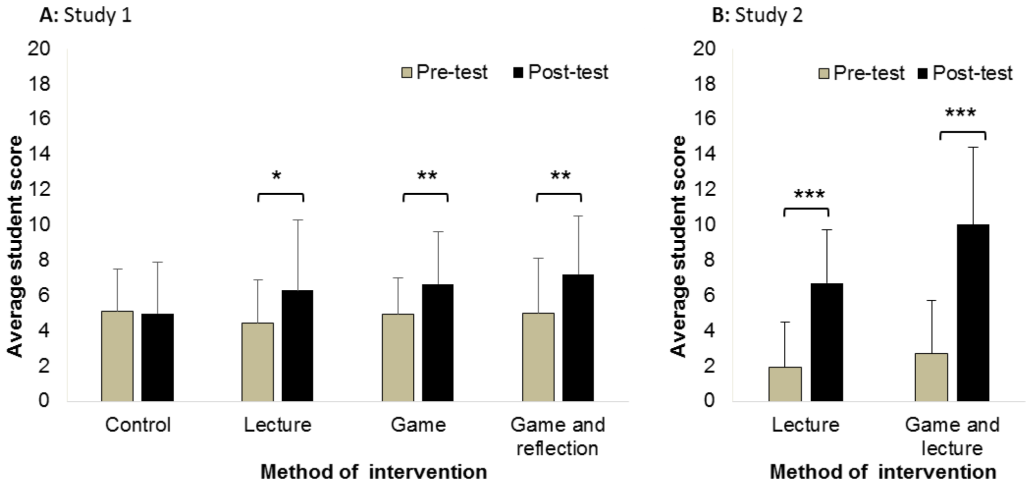

Figure 3: Comparison of student scores for the microbiology test before and after interventions. A: Study 1 shows effect of control (n=37), lecture (n=38), game (n=38) and game plus reflection (n=39) on score. B: Study 2 shows effect of lecture (n=95) and game and lecture (n=29) on score. Data shown is mean ± standard deviation. * indicates p ≤ 0.05, ** indicates p ≤ 0.01 and *** indicates p ≤ 0.001 in a paired samples *t*-tests.

To further investigate the depth of learning gains seen in study 2 (Fig. 3B), the test questions were grouped according to the thinking skill levels they were designed to test within Bloom's taxonomy. Given the small number of questions in each group, the six levels were divided into three groups and the increase in test scores for each group of questions was determined (Fig. 4).

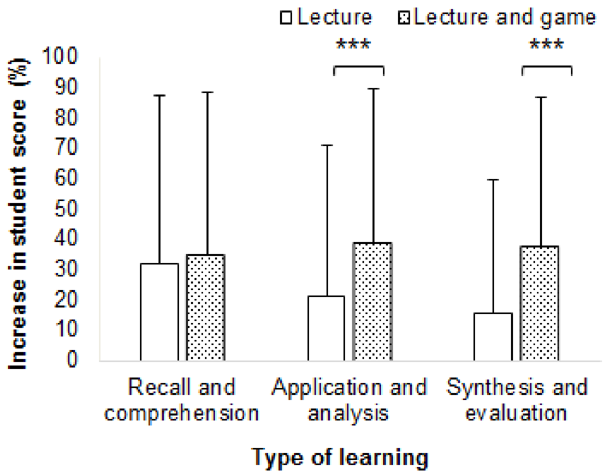

Figure 4: Comparison of increase in student score in different type of learning in Study 2. Test questions were grouped as recall and comprehension; application and analysis; and synthesis and evaluation and effect on score increase between lecture (n=95) and game and lecture (n=29) compared. Data shown is mean ± standard deviation. * indicates p ≤ 0.05, ** indicates p ≤ 0.01 and *** indicates p ≤ 0.001 in a student's non-paired t-test.

'Recall and comprehension', the lowest levels in Bloom's taxonomy, showed the highest increase in student score for those who only received the lecture, with higher order skills showing less of a score increase. Participants who experienced the game and lecture maintained a similar level of increase in all levels of learning. There was no difference in 'recall and comprehension' scores between the *lecture* group and *lecture plus game*, however there was a statically significant difference ~15% point increase in 'application and analysis' and ~20% point increase in 'synthesis and evaluation' for *lecture plus game* group, compared to the *lecture only* group.

To investigate the in-game activity of participants playing Bacteria Builder and the relationship to learning outcomes, the following analytics were collected from the gameplay; total time in game, number of star achieved, number of attempts at each environment, number of interactions in structure screen and time in shape and structures screen. This data was compared to the points increase in the in class test by regression analysis. Interesting there was no statically significant regressions between the quiz scores and game play analytics (data not shown).

7. Discussion

The results of Study 1 supported hypothesis A, with both the game and lecture conditions providing statistically significant learning gains from pre-to post test, when the control did not. The game and reflection condition was included because debriefing sessions have been considered by many to be critical to the effective application of educational simulations and games (e.g. Squire, 2002). However, in this study, very similar learning gains were observed from the game, both with and without the reflection. In contrast, the results of Study 2 demonstrated higher learning gains in the lecture and game condition compared to the lecture alone (supporting hypothesis B). This difference could simply be attributed to a longer period of teacher-led activity (15 mins reflection compared to 30 mins lecture), but might point towards the benefits of a multi-representational approach to learning (Ainsworth, 2008). Nonetheless, this does provide support for the value of Bacteria Builder as a teaching resource designed to supplement traditional teaching methods.

Perhaps more significantly, Study 2 was able to provide support for hypothesis C which suggested that the game would provide a greater improvement in questions that address higher order thinking skills as compared with the lecture alone. This is an important finding and one which provides empirical support for theoretical ideas about the potential benefits of constructivist game-based learning environments.

Finally, Study 2 was unable to provide any support for our final hypothesis (hypothesis D) which was that the level of interaction with the game will predict learning outcomes. This was a surprising finding given the positive learning outcomes produced during the study. Nonetheless, as a fixed-time on task study we should expect it to be harder to find proportional differences in learning. The team also feel that contrasting strategies may be hiding direct relationships between the primary analytical data, and a more complex analysis of the log data may provide additional insights into how payers were (or weren't) learning with the game.

8. Conclusion

Bacteria Builder was created to help undergraduate nurses gain a more in depth understanding of the form and function of bacteria as part of a university fundamental science module for first year trainee nurses. The results of this study show that it has succeeded in this aim and it represents a useful companion application to be used alongside traditional teaching. Furthermore, the study has provided empirical evidence that constructivist game-based learning approaches can provide additional benefits for higher-order thinking skills over traditional teaching approaches.

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