Serious Game Leverages Productive Negativity to Facilitate Conceptual Change in Undergraduate Molecular Biology:
A Mixed-Methods Randomized Controlled Trial

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ABSTRACT

We designed a serious game, MolWorlds, to facilitate conceptual change about molecular emergence by using game mechanics (resource management, immersed 3rd person character, sequential level progression, and 3-star scoring system) to encourage cycles of productive negativity. We tested the value-added effect of game design by comparing and correlating pre- and post-test misconceptions, interaction statistics, and engagement in the game with an interactive simulation that used the same graphics and simulation system but lacked gaming elements. We tested first-, second-, and third-year biology students’ misconceptions at the beginning and end of the semester (n = 526), a subset of whom played either the game (n = 20) or control (n = 20) for 30 minutes prior to the post-test. A 3x3 mixed model ANOVA revealed that, while educational level (first-, second-, or third-year biology) did not influence misconceptions from pre-test to post-test, the intervention type (no intervention, simulation, or game) did (p<.001). Pairwise comparisons showed that participants exposed to the interactive simulation (p = .007), as well as those exposed to the game (p<.001), lost significantly more misconceptions in comparison to those who did not receive any intervention, while adjusting for educational level. A trending difference was found between the simulation group and the gaming group (p = .084), with the gaming group resolving more misconceptions. Quantitative analysis of click-stream data revealed the greater exploratory freedom of the control simulation, with greater accessibility to individuals who do not play games on a regular basis. However, qualitative analysis of gameplay data showed that MolWorlds-players experienced significantly more instances of productive negativity than control-users (p<.001) and that a trending relationship exists between the quality of productively negative events and lower post-test misconceptions (p = .066).

KEYWORDS

Conceptual Change, Interactive Simulation, Molecular Biology, Productive Negativity, Randomized Controlled Trial, Serious Game
INTRODUCTION

Background

In molecular biology, students have difficulty understanding how random, seemingly inefficient, mechanisms contribute to the functioning of complex, perceptually efficient, cellular systems and often compensate by attaching agency, or directedness, to molecular species (Momsen et al. 2010; Chi 2005; Chi et al. 2012; Garvin-doxas & Klymkowsky 2008; Chi & Roscoe 2002). It is important that students can reconcile randomness at the molecular level with the perceived efficiency of cellular systems as this lends meaning to more complex concepts, such as concentration gradients, protein specificity, or cell signalling cascades, and how these mechanisms may affect health and disease outcomes. However, these misconceptions are often robust and resistant to change; it requires that the student recognize that her understanding is incorrect, be provided with the tools to build a new mental model, and have the motivation in the first place to do so (Chi 2005; Modell et al. 2005).

Serious games are engaging spaces for active learning that may provide students with the motivation needed to trigger conceptual change. Cycles of productive negativity encourage schema building and are common in gaming environments—the player is challenged by a task and, under her current conception, she fails and must restructure her understanding in order to succeed (Mitgutsch & Alvarado 2012). This process corresponds with Chi (2005)’s conceptual change strategy involving misconception confrontation and schema building. Additionally, common game mechanics can be leveraged to promote productive negativity. For example, in their subversive game “Afterland”, Mitgutsch and Alvarado (2012) employ inventory collection, health status, and enemy-evasion because they can predict how gamers will interact with and react to these mechanics. However, interaction with these leads to unexpected outcomes, resulting in productive negativity and a learning experience for the player. To generalize, serious games can apply commonly used mechanics in uncommon ways so that players behave predictably, increasing the chances for productive negativity—and conceptual change—to ensue.

Furthermore, game design mechanics and elements have potential to increase a student’s willingness to participate in meaningful and intellectual play, thereby enhancing her understanding of target content and concepts (Squire 2011; Steinkuehler & Squire 2012; Gauthier et al. 2015). Much literature supports video games for learning (Gee 2007; Landers & Callan 2011; Squire 2006), but the empirical evidence can be contradictory. Recent meta-analyses reveal that serious games can increase learning, self-efficacy, and motivation in comparison to traditional learning or other non-gaming stimuli (Wouters et al. 2013; Sitzmann 2011; Clark et al. 2016) but fail to highlight the value-added effect of game design (Clark et al. 2016). The present publication strives to contribute to this area by investigating the value-added effect of a serious game in relation to a simulation application that employs similar interaction and visual design. This study is also, to the best of our knowledge, one of the first to implement conceptual change strategies—specifically, productive negativity—through game design to address misconceptions in undergraduate science.

Research Objectives and Hypotheses

In this study, we compare and relate molecular misconceptions, game-play statistics, and player characteristics (e.g. level of education, gaming habits) among undergraduate biology students who engage with either a serious game or a ‘control’ interactive simulation. Specifically, we endeavoured to 1) facilitate conceptual change about molecular emergence through interactive media; 2) characterize how game design influences this phenomenon; and 3) explore how other factors such as perceived engagement with the app and player characteristics relate to interactions and, ultimately, learning.
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