OPEN ACCESS Freely available online

CourseSource

Lesson

A simple way for students to visualize cellular respiration: adapting the board game Mousetrap™ to model complexity

Meg Bentley and Victoria P. Connaughton,*

American University, Department of Biology, Washington D.C.

Abstract

Lecture-based introductory biology courses are typically content-heavy as instructors strive to provide students with foundational knowledge in a broad range of topics. One topic traditionally covered is cellular respiration, the series of enzymatic reactions that results in the formation of ATP, the energy currency in cells, from carbohydrates. Cellular respiration is often difficult for students in these classes because the topic is both complex and 'invisible' – the students can't observe the process. In an attempt to overcome these difficulties and enhance student learning, we describe how the board game Mousetrap™ (Hasbro, Milton Bradley) can be adapted to model cellular respiration. Mousetrap™ is ideal for this adaptation due to its 3-dimensionality, the necessary assembly of its 3D components and the interdependence of its 3D components. In the classroom, the pieces of the game are re-assigned into the three stages of cellular respiration (glycolysis, Krebs Cycle, electron transport chain); after each stage is discussed in lecture, students assemble that part of the board game. By the end of class, the game is completely assembled, providing students with a workable model of the entire cellular respiration pathway. Students then trigger the mousetrap to visualize the complete, dynamic process and 'make ATP' (i.e., catch the mouse). Mousetrap™ serves as a dynamic, interactive, active learning tool that helps students build a basic, but accurate model for cellular respiration that can be used as a scaffold for subsequent upper-level courses or for more complex discussions related to fermentation, toxicology, and/or enzymatic regulation.

Citation: Bentley, M., and Connaughton, V.P. 2017. A simple way for students to visualize cellular respiration: Adapting the board game Mousetrap™ to model complexity. *CourseSource.* https://doi.org/10.24918/cs.2017.8

Editor: Benjamin Martin, Stony Brook University, Stony Brook, NY

Received: 01/29/2016; **Accepted:** 07/19/2016; **Published:** 05/08/2017

Conflict of Interest and Funding Statement: None of the authors have a financial, personal, or professional conflict of interest related to this work.

Supporting Materials: S1. Mousetrap-Lecture, S2. Mousetrap - Names of the game pieces, and S3. Mousetrap - Relation of game pieces to cellular respiration

***Correspondence to:** Dept of Biology, Hurst Hall, Rm. 101, American University, 4400 Massachusetts Ave, NW, Washington, DC 20016

Learning Goal(s)

- Students will understand the complexity of the cellular respiration pathways.
- Students will understand the stages of cellular respiration.
- Students will understand the importance of cellular respiration for cell function.

Learning Objective(s)

- Students will be able to describe the three stages of cellular respiration.
- Students will be able to identify the reactants entering and the products formed during each stage of cellular respiration.
- Students will be able to explain how chemical energy in carbohydrates is transferred to ATP through the stages of cellular respiration.
- Students will be able to explain the effects of compartmentalization of cellular respiration reactions in different cellular spaces.
- Students will be able to predict biological outcomes when a specific stage(s) of cellular respiration is altered.

INTRODUCTION

General Biology I is the first in a two-course introductory sequence required of all Biology majors at American University. General Biology I is also a required course for students majoring in Biochemistry, Environmental Science, Environmental Studies, Public Health, Neuroscience, and Health Promotion; for students minoring in Biology and Biochemistry; and for students enrolled in the post-baccalaureate premedical program. The proportion of students enrolled in the course from each degree program in any given semester is highly variable, though more than half of the students are typically Biology and Public Health majors.

The course is lecture-based and content-heavy, covering topics in cellular and molecular biology, including structure and function of organelles, transcription and translation, DNA replication, cellular respiration, photosynthesis, mitosis and meiosis, membrane trafficking, and genetic engineering. This course is meant to provide our majors with the foundational knowledge necessary for success in upper-level courses. For non-majors, it may be the only Biology course they take during their undergraduate careers. Lecture classes range from 45-60 students; although this class size is somewhat large, it is small enough to facilitate group work and hands-on demonstrations during the 75-minute class time.

For cellular and molecular processes in particular, content in an introductory Biology course is commonly presented as a set of facts that students must memorize. One example of this approach is cellular respiration, a relatively complex series of enzymatic reactions that converts the chemical energy of carbohydrates, and sometimes lipids, into ATP, the energy currency of the cell (1). The importance of ATP in cellular function makes understanding this topic fundamental to students' conceptual framework of how cells function. While the traditional, lecture-based format is a common strategy for covering large amounts of material in many introductory classes, it is not student-centered and does not take advantage of active- or cooperative-learning. A lecture-only approach to learning complex processes like cellular respiration can result in students not fully understanding how the discrete concepts fit together and/or the students not being able to apply these concepts to predict how processes can be altered or regulated (2).

The textbook used in our General Biology I course (Freeman, latest edition), separates cellular respiration into three discrete stages: Glycolysis, Krebs Cycle (also known as TCA Cycle), and Electron Transport Chain/Oxidative Phosphorylation. These three stages are presented with a focus on what molecule(s) enter each stage and what molecule(s) are produced, thereby linking the three stages together. Common misconceptions related to cellular respiration generally include problems with understanding (a) the enzymatic steps that transfer chemical energy from carbohydrates to ATP; (b) why different stages of cellular respiration are in different cellular compartments; (c) when and how much ATP is generated during the multiple stages; and (d) the timing and integration of the three stages.

Strategies that help students visualize biological phenomena, especially molecular or "invisible" processes, have been shown to increase understanding in STEM disciplines (3, 4). These strategies can include virtual animations, static models, or manipulative models. The advantage of animations is that they demonstrate the dynamism of a cellular process, including how one step can lead to another or how positive and negative feedback work. A disadvantage of animations is that students often experience them as individuals rather than in a group. In addition, while many exceptional animations are available online, they are not adaptable for a teacher who may need to customize content for a variety of audiences. Research suggests that models can increase retention of information, especially strong when students generate a manipulative model (5).

Models can include physical 3D representations, for example a model of the heart or a mitochondrion. The advantage of physical models is that they transform material normally presented as 'flat' in a textbook or on a slide into multiple dimensions. In addition, multiple students can experience these 3D models simultaneously. A disadvantage of 3D models is that they are generally static or have minimal moving parts, overlooking the complexity of a biological system. Modeling can also include virtual animations or simulations of cellular processes. Current manipulative models for teaching cellular respiration typically include students color-coding chemical reactions (6), snap together beads, or magnetized boards with movable chemical structures and LEGOs, which have been shown to increase student performance and interest in this content area (7).

Here, we describe how we have adapted the children's board game Mousetrap™ (Hasbro, Milton Bradley) as a manipulative model to teach cellular respiration in our General Biology I lecture classroom. In brief, the pieces of the board game are re-assigned into the three stages of cellular respiration (Glycolysis, Krebs Cycle, Electron Transport Chain/ Oxidative Phosphorylation). After each stage is discussed in lecture, the students assemble that part of the game (see lecture PowerPoint, Supporting File 1). Once completely assembled, students have a workable model of the entire pathway in front of them. Students then trigger the mousetrap so they can visualize connections and "make ATP" (i.e. catch the mouse).

One advantage that adapting the Mousetrap™ board game has over other manipulative models is that students must follow a single, prescribed method to assemble a Mousetrap™ model of cellular respiration. As a result, it is easier for students to assemble a correct model, even in larger classes in which the instructor may have limited opportunity for individualized coaching. The fact that there is one correct assembly also lessens the possibility that students make mistakes in their modeling, which might reinforce misconceptions. In addition, this hands-on model provides students with a visualization that allows the instructor to discuss or challenge the students to think about how changing even a small part (or step in the pathway) can have a dramatic effect on the whole process. Questions that we have asked students to consider are 'What would happen if the electron transport chain was stopped by a toxin?' or 'How is ATP synthesis altered if the amount of pyruvate produced during glycolysis is reduced?' Thus, adapting the board game Mousetrap™ to model cellular respiration (a) takes advantage of the 3D representation of a cellular process; (b) allows students to cooperate and participate in building the model; (c) is dynamic; (d) is easily tunable for different audiences or student groups; and (e) can be used to make predictions.

Intended Audience

This lesson is used in introductory Biology courses suitable for majors and non-majors. Most recently, this lesson was used with first-year Biology majors at a liberal arts university.

Required Learning Time

The lesson is completed during class time as a supplemental, hands-on demonstration. The entire lesson takes a portion of one class period (75 minutes), with each component typically taking 5-10 minutes to complete (Table 1).

Pre-requisite Student Knowledge

Students should have knowledge of cellular organelles, specifically the mitochondria, and understand that phospholipid membranes create impermeable barriers between cellular compartments. Students should also know the significance of ATP as an energy currency, the definition of substrates, reactants and products, and that enzymes catalyze reactions.

Pre-requisite Teacher Knowledge

The instructor should understand the specific processes involved in cellular respiration, specifically the stages of Glycolysis, Krebs Cycle, and Electron Chain Transport/ Oxidative Phosphorylation. The lesson focuses on reactants entering each of these stages, the products that are formed, and how each stage progresses to the next. Teachers should understand that chemical energy is transferred through redox reactions and that the proton gradient generated by the Electron Transport Chain is responsible for driving ATP Synthase and phosphorylation of ADP to generate ATP, and that this final stage depends on the presence of oxygen.

SCIENTIFIC TEACHING THEMES

<u>Active learning</u>

Active learning occurs whenever students participate in an activity that allows them to process or synthesize course content. Here, the activity is students assembling game components meant to model content in lecture. After each stage (Glycolysis, Krebs Cycle, Electron Transport Chain/ Oxidative Phosphorylation) is presented in lecture, the instructor should pause to allow the students to assemble the game pieces corresponding to that stage (see PowerPoint lecture file, Supporting File 1). As students are assembling their model, they will visualize and discuss which components belong within each stage in the process. Upon completion of the model, students can visualize the entire process of cellular respiration and start to test the model.

<u>Assessment</u>

Lesson effectiveness can be determined using both formative and summative assessments. When the Mousetrap™ game is used in class, the teacher is walking around the room and interacting with the students, making sure they are linking the model to the different components of cellular respiration and asking them questions related to the model. Exams test content knowledge through a combination of multiple choice, short answer, and short essay questions.

<u>Inclusive teaching</u>

Inclusive teaching requires the intentional addition of activities that allow individuals to connect with each other to observe differences in learning and communication style and to see how others process and interpret content knowledge. The activity requires that students work together in small groups, providing an opportunity for peer-to-peer interaction and teaching. The activity engages both tactile and visual senses. When the model/game is triggered at the end of assembly, students discuss questions about cellular respiration and are encouraged to use the model to articulate their questions and defend their answers. Students taking STEM courses (8) frequently mention these changes to the traditional lecture classroom in surveys. The integration of active learning activities into the college classroom has been shown to enhance the learning of most students (2), and may be particularly effective for underserved and minority students (9, 10).

LESSON PLAN

The lesson plan includes the materials required, preparation, and a description of the lesson. A detailed timeline including all materials is included (Table 1). Preparation the first time the activity is taught takes at least one hour. Preparation for subsequent iterations takes approximately 15 minutes.

Preparation Before Class

We have found that groups of 2-3 students per game board works best, though we have also used groups of 5-6 students in larger classes. So, for a class of 30, anywhere from 5-10 copies of the Mousetrap™ game are needed. Before using the Mousetrap™ board game in class, the game board and pieces must be adapted. To do this, open each game box and separate all the pieces. Then, sort or divide the game pieces from each box into the three stages of cellular respiration: (1) Glycolysis, (2) Krebs Cycle, and (3) Electron Transport Chain/Oxidative Phosphorylation (Supporting File S2). Once separated, some pieces are labeled with a Sharpie marker (Supporting File S3) to represent specific reactants and/or products formed during each stage. Labeled pieces are put into individual Ziploc bags labeled Glycolysis, Krebs Cycle and ETC/Oxidative Phosphorylation, to facilitate use during class time. The instructor should write "ATP" on the mice; the mice are not associated with a stage of cellular respiration but are labeled to indicate the final product of the entire process, i.e. ATP. Separating and labeling of pieces allow students to keep track of what molecule(s) goes into each stage, what molecule(s) are formed during each stage, and how one stage is connected to the next.

The game board is also labeled (using post-it notes or stickers) to identify the three stages. A "Glycolysis (Step 1)" label is placed on the game board next to Base A (Supporting File S3). A "Krebs Cycle (Step 2)" label is placed adjacent to where the stairs fit into board (Supporting File S3). Finally, an "Electron Transport Chain (Step 3)" label is placed next to the slots for Base B (Supporting File S3).

We recommend that the instructor practice assembling the pieces, following the manufacturer's instructions, prior to using the game in class. The way some pieces fit together is not intuitive and it can take time for the students to determine how to correctly assembly the structures. Since the act of fitting pieces to the game board is not part of the content knowledge, we feel it is appropriate to help students with this task.

How to Play (using the game in class)

Students should work collaboratively to build their models. At the start of class, ask the students to open the game, place the game board on a flat surface, and remove the three bags of game pieces. The game is used as a model/hands-on

Table 1.Mousetrap - Description of the different activities involved in the game and the estimated time to complete each.

Activity	Description	Time
Preparation for Class		
Prepare games for handout in class	1. Separate pieces into appropriate steps 2. Label game pieces 3. Collect pieces for individual steps into ziploc bags	20-30 minutes (first time) ≤5 minutes (subsequent uses of the game) Initially, this step is longer because you must separate and label all game pieces. Each game can be reused, so subsequent preparation time is shorter.
Class Session		
Hand out game board	Begin class by handing out the games and asking the students to remove the game board, set it onto a flat surface, and identify the 3 labeled bags that contain the different pieces	3 minutes
Lecture	Explain glycolysis	10 minutes
Build Glycolysis	Students remove pieces from the bag marked 'Glycolysis' and assemble that part of the game	4 minutes
Lecture	Explain Krebs Cycle	10 minutes
Build Krebs Cycle	Students remove pieces from the bag labeled 'Krebs Cycle' and assemble that part of the game	4 minutes
Lecture	Explain oxidative phosphorylation	15 minutes
Build Oxidative Phosphorylation/ Electron Transport	Students remove pieces from the bag labeled 'Electron Transport Chain' and assemble that part of the game	4 minutes
Lecture	Discuss how all three steps work together, resulting in ~29 ATP molecules	5 minutes
Run the Model	Students trigger the model (turning the crank marked 'glucose') and watch as different pieces of the game occur, one following the next	5 minutes
Challenge the Model	Propose ways the model (pathway) could be disrupted, such as by a toxin targeting a specific step, and have the students remove that step/piece of the model and explain what will occur	10 minutes
Class Summary	Summarize the major points in lecture	5 minutes

demonstration to accompany lecture. Therefore, your lecture content can remain the same (see example PowerPoint lecture, Supporting File 1). After you introduce and describe a stage of cellular respiration, highlighting what molecule(s) enters and what molecule(s) leaves each stage, have the students assemble the corresponding part of the game. It is important to allow sufficient time (~5-10 minutes) for assembly of the different game pieces. The instructor may help the students with assembly, though we find that the students can usually work collaborative to successfully complete the assembly on their own.

Toward the end of lecture, when everything is assembled, we have students activate and test their model by "making ATP," i.e. students turn the crank labeled "glucose" that is listed in the Glycolysis section. This movement sets in motion a series of reactions they can follow culminating in the production of ATP (catching a mouse!).

TEACHING DISCUSSION

We used the Mousetrap™ exercise as a teaching aid in lecture to help students visualize the process of cellular respiration, to more easily conceptualize its reactants and products, and to use the terms associated with this process. To evaluate the effectiveness of the Mousetrap™ model teaching strategy, we compared student success on exam questions related to cellular respiration to student success on exam questions related to photosynthesis, which was taught in a traditional lecture format (IRB #2017-297 Category I Exemption).

We determined the percent of correct answers by students to multiple choice and short answer questions in an in-class, written exam. A comparison of exam questions related to cellular respiration and photosynthesis revealed no difference in the mean overall percent of correct answers between these two sets of questions (Mann-Whitney U test, $p = 0.6$; Figure 1A). However, in response to 'what was the hardest set of concepts on this exam?' ~40% of students responded "photosynthesis" compared to only 2% responded "cellular respiration" (Figure 1B); the concept to which the fewest number of students reported it being "the hardest concept" on the exam. Other concepts on the exam included mitosis and meiosis, which were also taught using traditional lecturing methods. When exam questions related to cellular respiration and photosynthesis are categorized by their Bloom's Taxonomy level, we find that 70% of students answered knowledge-level questions correctly for cellular respiration, and 80% answered these correctly for photosynthesis (Figure 1C). Comprehension-level questions were also answered correctly with similar frequency (both ~ 69% of correct answers, Figure 1C). The exam used to collect these data included just one analysis-level question on cellular respiration and none on photosynthesis, making a direct comparison between photosynthesis and cellular respiration impossible. However, we found that 72% of students answered the analysis-level question on cellular respiration correctly, indicating that as the Bloom's Taxonomy levels of questions increase, students' ability to choose the correct answer did not decrease.

We also performed an ungraded, pre-lecture quiz to determine prior knowledge. Though only 43% of the students completing the pre-test indicated they had learned about cellular respiration prior to coming to college, 78% correctly responded that cellular respiration occurs in

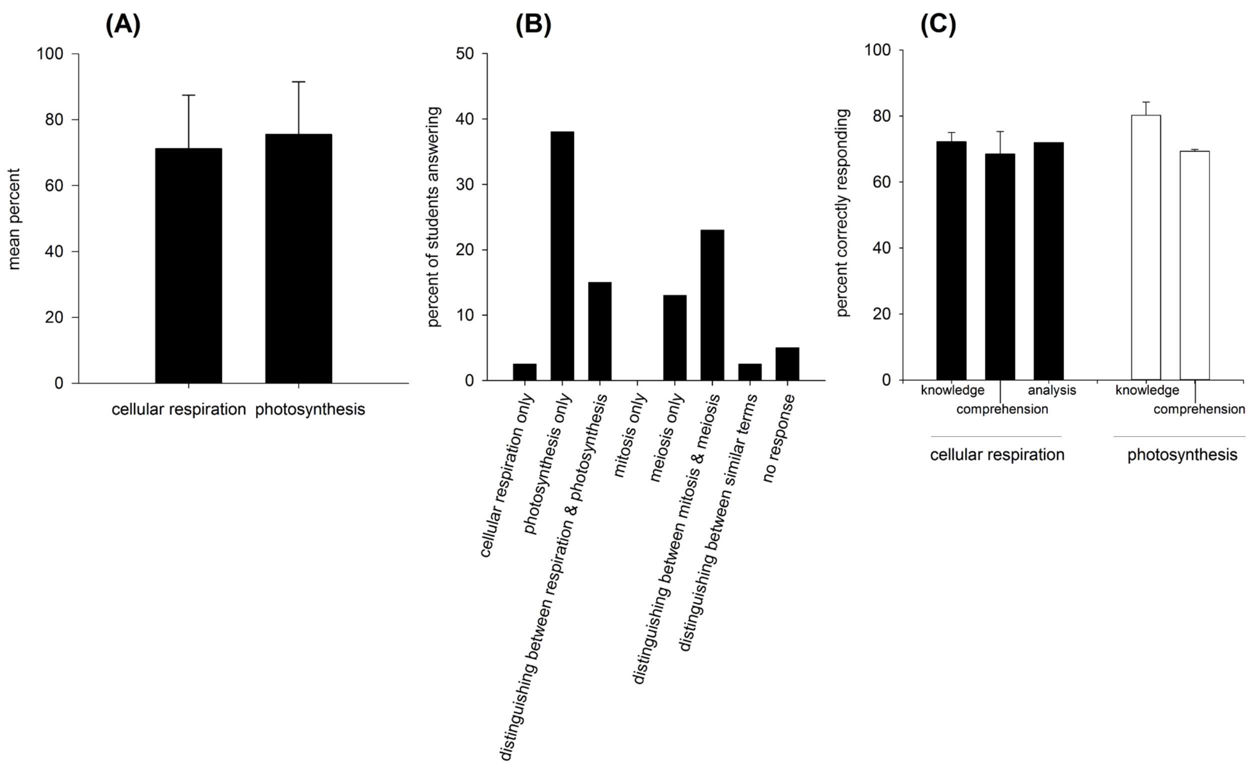

Figure 1. Assessment results. (A) The mean number of students who correctly answered questions on cellular respiration and photosynthesis in an in-class exam. **(B)** The number of students reporting that a particular concept on the exam was the hardest to learn (options beyond cellular respiration and photosynthesis were available). **(C)** Bloom's taxonomy level for cellular respiration and photosynthesis questions and the percent of students who answered these questions correctly. The % correct is based on the average of correct answers for all the questions at a particular level.

mitochondria, 76% knew that carbohydrates were the starting macromolecule, and 54% answered that ATP was produced during cellular respiration. The majority of respondents (63-68%) also knew the correct order of the stages of cellular respiration. The in-class demonstration therefore served to build-on this existing knowledge and to help the other students master this knowledge.

We have found that adapting the board game Mousetrap™ is an excellent way for students, especially in introductory biology classes, to visualize the molecules and processes of cellular respiration. Assembly of the different game pieces takes time and, in some cases, requires the students to stop and work with their group members to determine how they fit together. Assembling the game also requires that students vocalize cellular respiration terms introduced during lecture. When all the pieces are on the game board, the assembled structure is complex, which underscores the complexity of cellular respiration. Another benefit of adapting the Mousetrap™ board game as a model is that, once it is assembled, you can ask sophisticated questions, such as 'What would happen if there is no glucose in the bloodstream?' or 'How is ATP synthesis altered if ATP Synthase protein levels drop?' Thus, we feel confident that teachers' assessment questions can expand beyond the knowledge level of Bloom's Taxonomy. Directly visualizing how Glycolysis, the Krebs Cycle, and the Electron Transport Chain are linked together helps students to build a basic but accurate framework for cellular respiration. Upper-level classes can use this framework to scaffold additional concepts, including fermentation, toxicology, and enzyme regulation.

SUPPORTING MATERIALS

- S1. Mousetrap - Lecture
- S2. Mousetrap - Names of the game pieces
- S3. Mousetrap - Relation of game pieces to cellular respiration

ACKNOWLEDGMENTS

Thanks to all the students who participated in General Biology I at American University. Mousetrap™ is copyrighted and trademarked board game; manufacturer(s) are Hasbro, Milton Bradley. Hasbro is the current manufacturer and holds the copyright.

REFERENCES

1. Freeman S. 2014. Biological Science, 5th edition. Pearson/Benjamin Cummings.
2. Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci U S A 111:8410-8415.
3. Ainsworth S. 1999. The functions of multiple representations. Computers & Education 33:131-152.
4. Guzman K, Bartlett J. 2012. Using simple manipulatives to improve student comprehension of a complex biological process. Biochemistry and Molecular Biology Education 40:320-327.
5. Lazarowitz R, Naim R. 2013. Learning the cell structures with three-dimensional models: students' achievement by methods, type ofs chool and questions' cognitive level. J Sci Educ Technol 22:500-508.
6. Geisler B. 2013. Visualizing photosynthesis and cellular respiration. http://serc.carleton.edu/sp/mnstep/activities/38025.html. Accessed Sept 8, 2016.
7. Boomer SM, Latham KL. 2011. Manipulatives-based laboratory for majors biology - a hands-on approach to understanding respiration and photosynthesis. J Microbiol Biol Educ 12:127-134.
8. Science AAftAo. 2011. Vision and change in undergraduate biology education a call to action. Washington, DC.
9. Haak DC, HilleRisLambers J, Pitre E, Freeman S. 2011. Increased structure and active learning reduce the achievement gap in introductory biology. Science 332:1213-1216.
10. Eddy SL, Hogan KA. 2014. Getting under the hood: how and for whom does increasing course structure work? CBE Life Sci Educ 13:453-468.