RESEARCH ON LEARNING

Molecular Sculpting: Active Learning of Subcellular Systems & Processes

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ABSTRACT

Students often struggle to understand the complex molecular systems and processes presented in introductory biology courses. These include the Calvin cycle, the Krebs cycle, transcription and translation, and DNA replication, among others. Traditionally, these systems and processes are taught using textbook readings and PowerPoint slides as lecture aids; video animations have also become popular in recent years. Students tend to be passive observers in many of these methods of instruction, relying heavily on "memorization" learning techniques. To address this, I developed an active-learning intervention called "molecular sculpting" in which students construct two-dimensional or three-dimensional versions of an assigned molecular system or process, complete with representations of proteins, chromosomes, electrons, protons, and other molecules (depending on the system). The value of this learning activity was measured in five class sessions in an introductory biology course during the 2014–2015 academic year. Pre- and post-class written assignments showed that students were often able to describe course concepts more completely after sessions in which sculpting was used, compared with sessions without sculpting. Molecular sculpting is a unique, hands-on activity that appears to have significant learning gains associated with it; it can be adapted for use in a variety of K–14 biology courses.

Key Words: *Active learning; molecular biology; photosynthesis; cellular respiration; DNA replication; central dogma.*

○ Introduction

Many biology educators make concerted efforts to improve the quality of teaching and learning in their biology courses (Wood, 2009). Peer discussions, case studies, inquiry-based learning, and learning activities that incorporate authentic research have become more commonplace, as evidence continues to emerge in support of these high-value pedagogical approaches (Gelbart and Yarden, 2006; Weaver et al., 2008; Armbruster et al., 2009; Smith et al., 2009). This, combined with a call by the American Association for the Advancement of Science (AAAS, 2011) to integrate the teaching and learning of biological concepts across scales, has begun to change the face of biology learning in higher education. This is timely, because many students struggle with the articulation of complex microbiological systems and processes (Crane & Winterbottom, 2008; Panijpan et al., 2008; Patro, 2008; Shi et al., 2010). These systems and processes range from the anatomy and function of cells to information storage and processing (e.g., mitosis, meiosis, DNA structure and replication) to energy production (e.g., photosynthesis and respiration).

Introductory cell and molecular biology (i.e., microbiology) curriculum presents a unique challenge because it requires students to learn processes describing interactions among unfamiliar objects (i.e., proteins and molecules) in an unfamiliar system (i.e., a subcellular world). This differs from an introductory macrobiology curriculum in which concepts and processes are often presented using familiar objects (e.g., birds, fish, mammals) in familiar systems (e.g., trees, water bodies, ecosystems). In this way, a microbiology curriculum is somewhat analogous to a chemistry curriculum, in which student learning often involves the visualization of the geospatial orientation of molecules. Chemistry learners sometimes use stick-and-ball chemical model kits as learning aids; however, no such resources are widely used for the learning of microbiological systems.

Student visualization of complex microbiological systems and processes has traditionally been stimulated using passive pedagogies.

Student visualization of complex microbiological systems and processes has traditionally been stimulated using passive pedagogies. Textbooks provide a descriptive account of these systems, paired with artistic representations of proteins, molecules, and cell features. These are often the basis of reading assignments, even though "reading" is not a learning activity typically associated with notable learning gains (Benware & Deci, 1984). Similarly, instructor-centered explanations of these systems using PowerPoint slides are of limited use in stimulating deep

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learning (Levasseur & Sawyer, 2006). Recently, various publishers and educational groups have begun making detailed animations of subcellular processes (e.g., BioFlix: http://www.pearsonhighered.com/mybiology/bioflix.html; Virtual Cell: http://vcell.ndsu.nodak.edu/animations). These can be an important resource, because video animations are generally superior to static images as learning aids (Münzer et al., 2009). That said, watching instructional videos – similar to reading a textbook, or watching an instructor's PowerPoint presentation – is not generally considered to be an active-learning exercise (Schank, 1994; Prince, 2004; Felder & Brent, 2009).

The value of active-learning pedagogies has been consistently demonstrated in biology and across STEM disciplines (Udovic et al., 2002; Prince, 2004; Freeman et al., 2007); what remains is to develop high-value in-class activities to help facilitate the active-learning approach. In response to this need, I developed an in-class activity called "molecular sculpting" in which students work in teams to make two-dimensional and three-dimensional models of molecular systems out of modeling clay. They use their models to demonstrate class learning outcomes. I implemented this activity in an introductory cell and molecular biology course and collected data on student perception, student confidence, and student learning gains during molecular sculpting sessions. The project was reviewed and approved by the Michigan State University Institutional Review Board (IRB no. x13-1181e).

○ Description of Molecular Sculpting

What Is Molecular Sculpting?

Molecular sculpting is an in-class activity in which students work in pairs to create two-dimensional and three-dimensional sculptures of subcellular systems out of modeling clay or Play-Doh (Figure 1). During each 45- to 60-minute sculpting session, students are given a list of components they are to incorporate into their sculpture, along with one or more learning outcomes to achieve.

What Materials Are Needed for Molecular Sculpting?

Students are required to purchase their own modeling clay or Play-Doh at the beginning of the semester (e.g., six small jars of clay or Play-Doh). The instructor can also provide foam core boards and/or posterboard for students to create their sculptures on; the instructor may then encourage students to label their board to indicate various cell components and to add additional written detail (e.g., arrows to indicate the movement pathway of a molecule). The foam core and posterboard are optional; students can create their sculptures directly on standard classroom desks.

When & How Is Molecular Sculpting Used?

Molecular sculpting is used as an active classroom pedagogy. I have used molecular sculpting primarily after students have had at least one class session of teaching and learning on the molecular system or process to be sculpted. With the ~100 students in my intro-level cell and molecular biology course, I use the sculpting activity between four and six times throughout a semester to help students learn about eukaryotic cell structure, DNA structure, DNA replication, transcription and translation, photosynthesis, and cellular respiration. Because

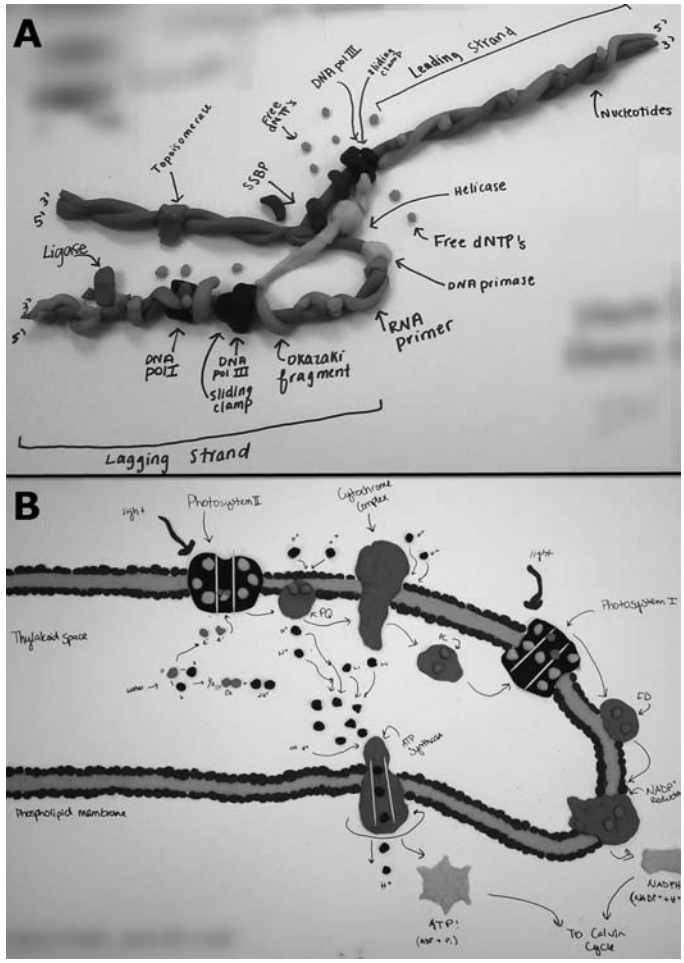

Figure 1. Examples of three-dimensional and two-dimensional student molecular sculptures for (**A**) DNA replication and (**B**) the light reactions of photosynthesis.

my course has both lab and lecture components, I invite the lab teaching assistants (typically graduate and/or undergraduate students) to join me during sculpting sessions to circulate around the classroom to answer student questions. Students are not awarded grade points for the quality of their sculptures.

Student Feedback

In the spring 2015 semester, my class of 99 students was given an anonymous midsemester online survey regarding their perception of learning gains associated with molecular sculpting. They were asked the question "How much did molecular sculpting help your learning?" Of the 69 students who responded, 28% felt that it was of "great help," 26% felt it was of "much help," 28% felt it was of "moderate help," 14% felt it was of "little help," and 4% felt it was of "no help."

Unfortunately, a summative, end-of-semester survey of molecular sculpting was not completed in 2015. However, in the spring 2013 semester, students in the same introductory cell and molecular biology course were asked two end-of-semester evaluation questions regarding molecular sculpting. Student responses were anonymous and the data were not shown to the instructor until after the final course grades were submitted. Students were asked to indicate how much they agreed with the following two statements, using a

five-point Likert scale (strongly agree, agree, neutral, disagree, strongly disagree):

- Statement 1:Molecular sculpting sessions helped me better understand the systems we learned in this course (e.g., photosynthesis, cellular respiration, DNA replication, central dogma).
- Statement 2: Molecular sculpting should be used in future iterations of [this course].

Of the 79 students enrolled in the class that semester, 72 responded. Of these, 71% "strongly agreed" or "agreed" that molecular sculpting sessions helped them better understand the systems learned in the course; 13% were "neutral" on the use of molecular sculpting; and 17% of students felt that sculpting did not help their learning (i.e., they "disagreed" or "strongly disagreed" with statement 1). Similarly, 71% of students felt that future iterations of the course should use molecular sculpting; 14% answered "neutral"; 15% "disagreed" or "strongly disagreed."

Molecular Sculpting, Student Confidence & Student Learning

I measured how student confidence and student learning were stimulated by standard class sessions versus molecular sculpting class sessions in the spring semester of 2015 (Figure 2).

Standard Class Sessions

In preparation for standard class sessions, students were asked to read 7–20 pages of their textbook before coming to class (Table 1). Each standard class session would begin and end with a 3-minute writing exercise and featured between 38 and 46 minutes of combined lecture plus "chalk talk" (Table 1). "Lecture" was a standard, traditional, teacher-centered pedagogy, using PowerPoint slides as visual aids. "Chalk talk" was also a teacher-centered pedagogy in which course content was written out by the instructor, on the classroom whiteboard. The "chalk talk" pedagogy was therefore marginally more interactive than the "lecture" pedagogy because students were encouraged/required to make their own handwritten notes of the processes and systems being detailed on the whiteboard. Furthermore, in every class session, students were given between 6 and 15 minutes of peer discussion, typically requiring them to discuss a system or process, or solve a problem, working in teams of two (Table 1). Most standard class sessions also featured one or two short videos, typically narrated animations that exhibited the process or system that was being presented in class. Finally, each class featured up to 24 minutes of time characterized as "miscellaneous" (Table 1). This time was spent on items ranging from discussing lab work to reviewing a midterm exam to reviewing content from a prior class.

Molecular Sculpting Sessions

Prior to a molecular sculpting session, students were asked to "come to class prepared to make a 2D or 3D molecular sculpture of [system X]." Students were permitted to bring visual aids to class to help them complete their sculpture but were told that they may be required to explain the system to the course's instructor or to one of the course's learning assistants who may be in attendance. Each molecular sculpting session would begin and end with a 3-minute writing exercise (Table 1). Lectures and chalk talks were used sparingly in molecular sculpting sessions – between 8 and 12 minutes – typically to give a very brief recap of the system they were to sculpt that day (Table 1). Peer-to-peer

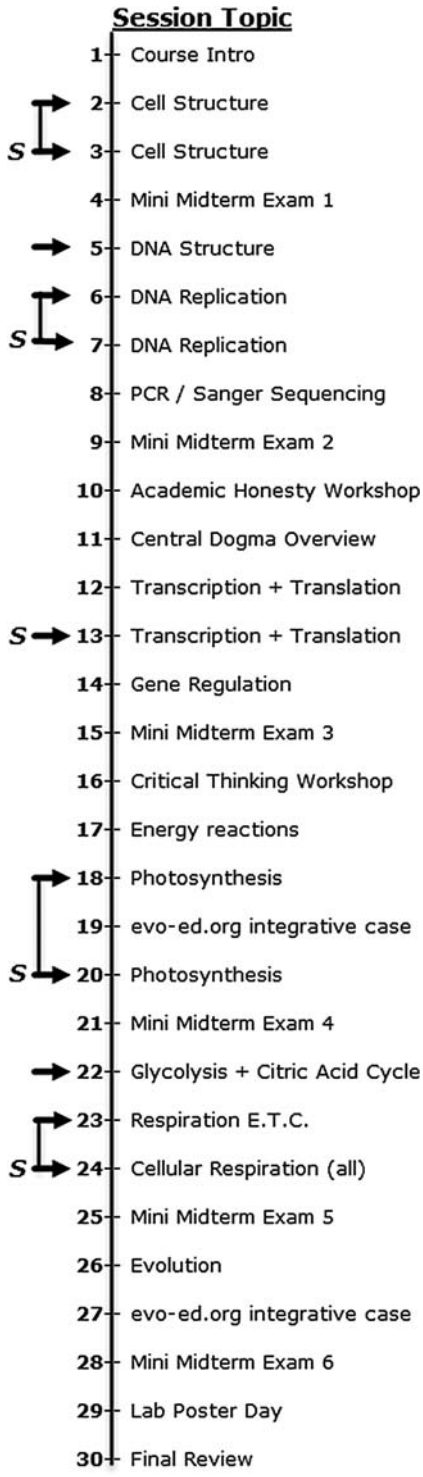

Figure 2. An overview of the cell and molecular biology course in which "molecular sculpting" was tested. Student confidence gain and learning gain were measured in 10 class sessions throughout the semester, as indicated by the arrows. Arrows with an ***S*** indicate molecular sculpting sessions; plain arrows indicate standard class sessions (for a description of what these two types of class sessions entailed, see Table 1). Linked arrows indicate consecutive sessions where student confidence and learning were assessed in subsequent sessions on the same system or process. All classes were 80 minutes in length.

Table 1. Student confidence and student learning were measured in 10 classes in the spring of 2015. Five of these were standard class sessions and five were "molecular sculpting" sessions. Each 80-minute class session had varying degrees of time dedicated to student writing (W), lecture + "chalk talk" (L + C), student discussion (D), videos (V), sculpting (S), and miscellaneous items (M) such as relating lecture sessions to lab content, reviewing midterms, or recapping topics learned in prior class sessions.

Session Number	Session Type	System or Process	Assignment Given to Prepare for Class	Minutes for In-Class Activities					
				W	L + C	D	V	S	M
2	Standard	Cell Structure	Read 17 pages of textbook	6	30 + 5	10	9	0	19
3	Sculpting	Cell Structure	"Prepare for sculpting"	6	12 + 0	5	4	50	3
5	Standard	DNA Structure	Read 15 pages of textbook	10	0 + 38	8	0	0	24
6	Standard	DNA Replication	Read 17 pages of textbook	11	5 + 41	10	0	0	12
7	Sculpting	DNA Replication	"Prepare for sculpting"	6	10 + 0	0	8	52	4
13	Sculpting	Transcription + Translation	"Prepare for sculpting"	11	2 + 0	4	0	50	13
18	Standard	Photosynthesis	Read 20 pages of textbook	10	35 + 3	15	8	0	6
20	Sculpting	Photosynthesis	"Prepare for sculpting"	6	5 + 3	3	3	50	10
23	Standard	Respiration ETC	Read 7 pages of textbook	6	25 + 15	6	6	0	20
24	Sculpting	Respiration ETC	"Prepare for sculpting"	6	10 + 0	0	0	50	12

discussion and videos were also used sparingly. The bulk of the class time in sculpting sessions (~50 minutes) was dedicated to the sculpting activity (Table 1).

Molecular Sculpting & Student Confidence

Student confidence was measured using pre- and post-class clicker questions during class sessions in which six different course systems or processes were taught and/or learned: (1) cell structure and function, (2) DNA structure, (3) DNA replication, (4) transcription and translation, (5) photosynthesis, and (6) cellular respiration (Figure 2).

Before these class sessions, students were asked the following clicker question:

- Given what you have learned to date, how confident are you that you know what you need to know about [system X]?

  [Very Confident] [Confident] [Unsure] [Unconfident] [Very Unconfident]

Similarly, at the end of these class sessions, students were asked:

- Given what you have learned in class today, how confident are you that you know what you need to know about [system X]?

  [Very Confident] [Confident] [Unsure] [Unconfident] [Very Unconfident]

Prior to standard class sessions, student confidence ranged between 6% and 51% (average = 26%; top portion of Figure 3), rising to between 29% and 62% (average = 43%; top portion of Figure 3) once the session was over. Prior to molecular sculpting sessions, student confidence ranged between 28% and 68% (average = 43%; top portion of Figure 3), rising to between 46% and 82% (average = 61%; top portion of Figure 3) once the session was over. It is notable that the average confidence gain is nearly identical between class session types: 17% in standard class sessions (i.e., from an average of 26% to an average of 43%) compared with 18% in molecular sculpting sessions (i.e., from an average of 43% to an average of 61%).

Molecular Sculpting & Student Learning Gains

Learning gains were measured using an open-ended writing exercise at the beginning and again at the end of the same class sessions in which student confidence was measured (described above; see also Figure 2).

Before these class sessions, students were asked the following open-ended question:

- Describe what you have learned to date about [system X].

After these class sessions, students were asked the following open-ended question:

- Describe what you learned in class today about [system X].

In each case, students were given 3 minutes to write their responses. They were asked to put away all course materials prior to the exercise; it was treated like a quiz though no course points were directly assigned to these exercises (students were given a very small allotment of points in the semester for "in-class preparation and participation"; some students may have associated it with this activity).

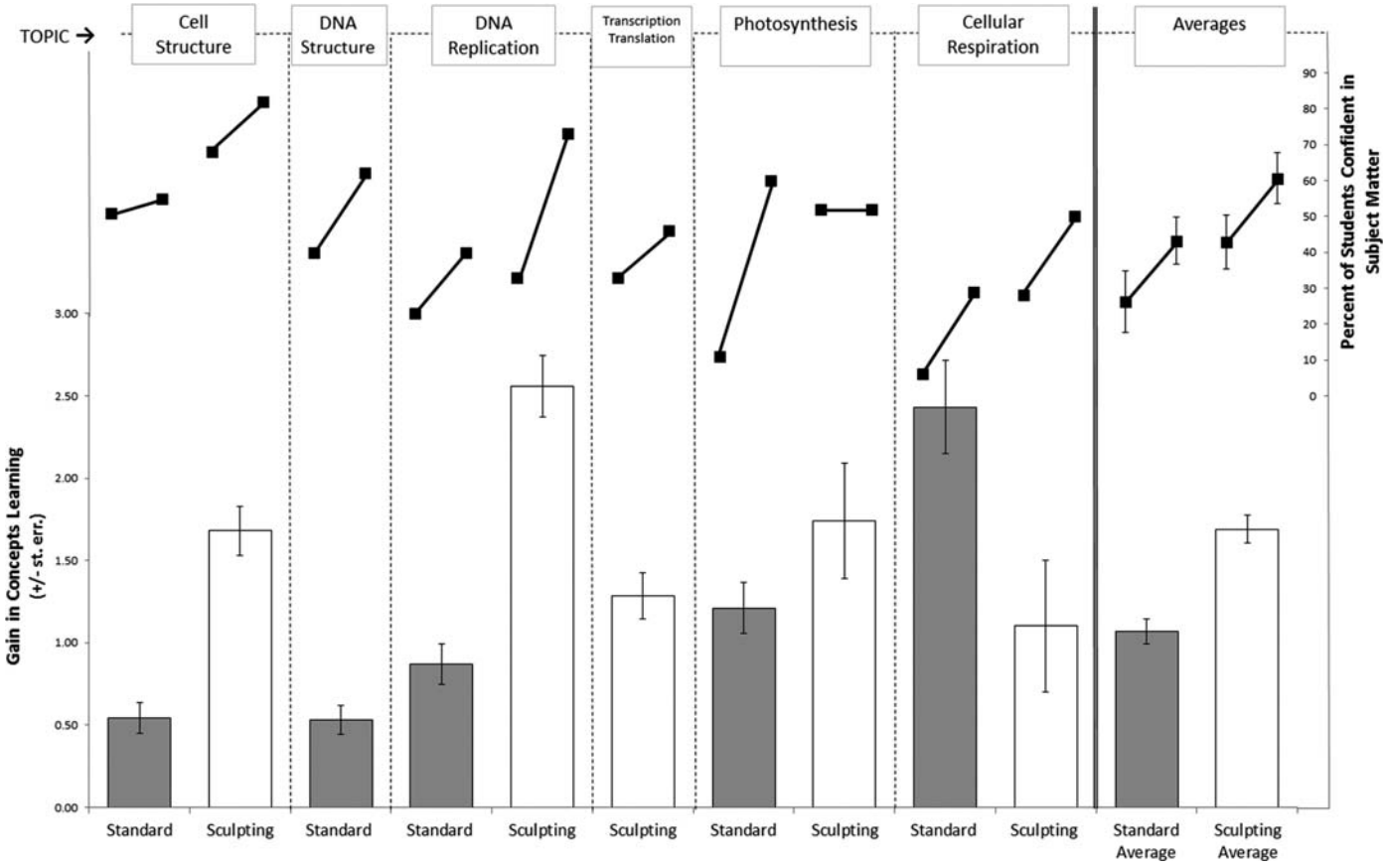

Figure 3. Student learning and student confidence associated with standard and "molecular sculpting" classes in introductory cell and molecular biology, showing gains in concept learning associated with each class throughout six topics. The upper (line) portion of the graph shows the student confidence from the beginning to the end of each class session, connected with a straight line.

Learning during these class sessions was measured as the number of concepts and/or system details that students wrote on their end-of-class writing exercise (for a detailed rubric, see Appendix 1). Each writing exercise was scored +1 point for each concept or detail that students correctly described. If a student repeated an item that they had previously written about, whether it was from a written assignment in a previous class session or from the pre-class assignment on the same day, they were not given credit for that item. Hence, a measure of learning *gain* was calculated for each of these class sessions examined.

Calculating learning gain using this method, students gained an average of 1.1 new concepts following a standard class session and an average of 1.6 new concepts following a molecular sculpting session (Mann-Whitney test, $P < 0.0001$; Figure 3, lower portion). Students demonstrated a larger gain of concepts during molecular sculpting sessions on cell structure and DNA replication, compared with standard class sessions on the same topic (Mann-Whitney test, $P < 0.0001$ for each of the two comparisons; Figure 3). Conversely, students demonstrated a larger gain of concepts during the standard class session on cellular respiration, compared with the molecular sculpting session on the same topic (Mann-Whitney test, $P < 0.0001$; Figure 3). There was no statistical difference in the gain of concepts with respect to photosynthesis between the standard class session and molecular sculpting session (Mann-Whitney test, $P = 0.22$; Figure 3).

Discussion

Overall, the data indicate that molecular sculpting is a valuable learning activity. Students felt that it was helpful to their learning and recommended that it be used in future course iterations. Student confidence gains following molecular sculpting sessions were comparable to student confidence gains following standard class sessions (Figure 3). Generally, student writing demonstrated similar or larger learning gains associated with molecular sculpting sessions, compared with standard class sessions (Figure 3). In the context of this study, molecular sculpting was tested as a student-centered classroom activity designed to be incorporated within an interactive pedagogical approach; it is not necessarily being proposed as a replacement for existing classroom pedagogies.

Three notable patterns emerged in the learning-gains data (Figure 3). The molecular sculpting session yielded larger concept-learning gains than the standard session for both the cell structure and DNA replication topics. There was no statistical difference in learning gains between the two class types during the photosynthesis topic. The molecular sculpting session yielded smaller conceptual learning gains than the standard session for the cellular respiration topic. It is unclear why these three different patterns emerged in the data; I am unaware of any pedagogies I used in the classroom during the presentation of cellular respiration that differed from other

standard class sessions (see Table 1). Though student learning gains were smaller during the respiration sculpting session, there was still a 22% increase in student confidence over the duration of that class session (from 28% to 50%); this is nearly identical to the 23% increase in student confidence (from 6% to 29%) measured from the beginning to the end of the prior standard session on respiration. Overall, the data indicate that sculpting class sessions stimulate both student learning gains and student confidence gains – in most cases comparable to, or exceeding, those stimulated by standard class sessions.

There are several challenges involved in implementing the sculpting activity. One of the first challenges can be student perception. Many students may not be eager to engage in an activity that uses Play-Doh or modeling clay; to some, it can feel juvenile at a time in their lives when they see themselves as maturing into adulthood. I try to ameliorate this by using the name "molecular sculpting" for the activity and, initially, by recommending that students use modeling clay rather than Play-Doh. I also strongly suggest that instructors provide learning outcomes to students prior to this activity. The use of learning outcomes makes it clear to students that this is a learning activity. For example, in the molecular sculpting session for photosynthesis, I often use the following learning outcome: "By the end of today's sculpting session, you should be able to demonstrate how photons of light are used to generate NADPH and ATP at a thylakoid membrane, within a chloroplast."

While attempting to master this outcome, students are encouraged to move components within their sculpture to mimic the movement of photons, electrons, protons, ATP molecules, NADH molecules, and other carbon compounds within the photosynthetic systems and processes.

Another challenge that students sometimes face during this activity is staying on task. Inevitably, a small proportion of students become sidetracked using social media applications on their cell phones or become preoccupied in engrossing conversations with peers that shift their focus away from their sculpting work. To counteract this, I become a very active presence in the classroom. I typically walk around the classroom, stopping at various student groups to ask simple questions, such as "So, tell me about the sculpture you're making" or "Do you have any questions about what you've made?" or, particularly near the end of the sculpting session, "Can you use your sculpture to show me how NADPH and ATP are made?" (i.e., the learning outcome of the day.) This type of instructor–student interaction is an integral part of active and/or flipped classrooms in which long stretches of time are allotted for student problem solving and collaborative assignments (Demetry, 2010; Tucker, 2012); this strategy should be integrated as part of the molecular sculpting activity.

Although this activity has been well received by most students, there has been a smaller percentage of students in each semester who find the activity of little or no value. In 2013, only 71% of students found molecular sculpting helpful to their learning; in 2015, only 82% of students found sculpting at least "moderately helpful" to their learning of a given molecular system. In other disciplines, with varying types of pedagogies, positive attitudes toward the active and/or flipped classroom approach seem to range around 70–80% (Bates & Galloway, 2012; Butt, 2014; Love et al., 2014). The student perception of the value of molecular sculpting that I measured in this work fits within that range. Speculatively, this may suggest that resistance to the sculpting activity may have much to do with the active-classroom pedagogical approach, rather than the molecular sculpting activity per se.

While this work represents something of a pilot study on the molecular sculpting activity, initial results indicate that it has promise as a valuable learning tool in an active and/or flipped classroom context. I have used it in classes with as few as 10 students and in classes with as many as 100 students. It may be a challenging in-class activity to implement in large classrooms (i.e., >200 students), though instructors who are experienced with an active and/or flipped classroom approach in large classes may find it appropriate. It is likely to have pedagogical applications in courses beyond introductory cell and molecular biology. For example, it could be used to sculpt anatomical systems, neurons and sensory systems, complex biochemical reactions, species interactions, ecosystem-level processes, or population-level processes. It can readily be used in a variety of class contexts and is easily adaptable for use in a variety of biology and chemistry courses.

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Appendix

Below are the scoring criteria for the student pre- and post-class written assignments. The written assignments were scored 1 point for each item on the list that students correctly listed. These lists were not shown to students.

If students repeated an item that they had previously listed, whether it be from a previous written assignment or from a pre-class assignment on the same day, they were not given credit for that item.

Topic 1: Cell Structure

1. Membranes are semi permeable
2. Membranes are made of phospholipids
3. Phospholipids have hydrophobic and hydrophilic regions
4. Lipids include phospholipids, steroids and fats
5. Steroids (e.g., cholesterol) change the permeability and fluidity of a membrane
6. Unsaturated fatty acid chains (or phospholipids) have double bond(s) in them somewhere (Saturated do not)
7. Nucleus has two membranes and holds DNA
8. Ribosomes manufacture proteins
9. The Rough ER has pores where protein can be manufactured
10. A vesicle can bud off the Rough ER and move to the Golgi apparatus
11. Proteins are modified at the Golgi apparatus.
12. A vesicle can bud off the Golgi and fuse with the cell membrane or another organelle
13. The Smooth ER synthesizes lipids and/or detoxifies harmful substances
14. The lysosome digests old organelles or foreign matter (or have lots of H+)
15. The peroxisome breaks down carbon chains (or related to "digestion" of cellular molecules)
16. Mitochondria creates ATP "energy"
17. Chloroplasts intercept light and manufactures sugar
18. Cell wall provides structure
19. The cytoskeleton (or microtubules) provide structural support and facilitate the transport of molecules
20. Kinesin is a transport motor protein.
21. mRNA is made from DNA
22. Protein is made from mRNA
23. Vacuole is for water regulation and storage

Topic 2: DNA Structure

1. DNA is made of a sugar-phosphate backbone (or ribose-phosphate)
2. DNA provides a template for RNA production
3. The bases are A, C, T, G (may write out full names, but do not need to; Adenine, Guanine, Cytosine, Thymine)
4. A and G are purines
5. C and T are pyrimidines
6. A pairs (H-bonds) to T
7. C pairs (H-bones) to G
8. RNA has U(racil) instead of T(hymine)
9. DNA strands are anti-parallel
10. ATP resembles a nucleotide
11. A nucleotide of DNA has a 5' phosphate group on the ribose.
12. A nucleotide of DNA has a 1' nitrogenous base on the ribose.
13. A nucleotide of DNA has a 3' OH group on the ribose.
14. A nucleotide of DNA lacks a 3' OH group on the ribose.

Topic 3: DNA Replication

1. There is a leading strand and a lagging strand.
2. Helicase separates DNA
3. Topoisomerase relieves tension, or stabilizes DNA
4. Single stranded binding proteins (or SSBP) stabilizes the DNA or it keeps DNA separated.
5. DNA Polymerase III (DNA POL III) adds nucleotides
6. Sliding clamp stabilizes the replication process (or holds DNA Polymerase III onto the DNA)
7. Primase adds RNA primer
8. Ligase joins Okazaki fragments OR Ligase joins gaps in DNA
9. DNA Polymerase I replaces RNA primer with DNA.
10. Replication enzymes are grouped together in a *replisome*.
11. Replication happens in a 5' to 3' direction
12. Telomerase builds telomeres at the end of linear chromosomes on the lagging strand.
13. Okazaki fragments are small fragments of DNA; occur on the lagging strand.

Topic 4: Transcription and Translation

Transcription

1. Initiation is where RNA Polymerase (RNA POL) binds to promoter region
2. Promoter region is -10 and -35 box in prokaryotes
3. Promoter region is TAT box in eukaryotes
4. Sigma factor helps RNA POL binding in prokaryotes
5. Transcription factors help RNA POL binding in eukaryotes
6. Elongation is where RNA POL builds an RNA strand
7. The template strand is read and built upon
8. Termination occurs via a hairpin loop in prokaryotes
9. Termination occurs via a polyadenylation sequence in eukaryotes

Post-Transcript Modification

1. Post-Transcript modification occurs in eukaryotes only
2. A 5' cap is added

3. A 3' tail is added
4. Introns are spliced out by spliceosomes

Translation

1. Initiation starts when mRNA binds to the rRNA on the small subunit of the ribosome.
2. The large subunit attaches
3. Translation starts at the START codon
4. tRNA carries amino acids to the ribosome
5. tRNA reads mRNA codon
6. new tRNA enters the A-site of the ribosome
7. Peptide bond is formed between amino acids
8. tRNA in P-site shifts to E-site; tRNA in A-site shifts to P-site.
9. Stop codon ends process via a release factor.
10. At the stop codon, a termination factor enters the ribosome and hydrolyzes the end of the amino acid chain
11. Large subunit has 3 site E P A
12. Transcription and Translation happen at same place in prokaryotes

Topic 5: Photosynthesis

1. Names of *Photosystem II*, *plastoquinone (pq)*, *cytochrome complex, plastocyanin (pc), Photosystem I, ferredoxin (fd), NADP+ reductase*
2. H_2O is split to make O_2 and 2 H^+
3. H_2O donates electrons (e^-) to photosystem II
4. Electrons travel from *Photosystem II → pq → cytochrome complex → pc → Photosystem I → fd → NADP+ reductase*
5. Light photons stimulate electrons at PSI
6. Light photons stimulate electrons at PSII
7. 4 H+ cross the membrane
8. $NADP^+$ + H → NADPH
9. H^+ travel out ATP synthase
10. ADP → ATP (at ATP synthase)
11. ATP and NADPH go to the Calvin Cycle
12. CO_2 enters the Calvin Cycle
13. RuPB converted to 3-Phosphoglycerate (3PG)
14. 3-Phosphoglycerate (3PG) is converted to glyceraldehyde 3-phosphate (G3P
15. As 3PG → G3P, 6 ATP → 6 ADP
16. As 3PG → G3P, 6 NADPH → 6 $NADP^+$
17. 5 G3P recycled, one comes out
18. 5 G3P → 3 RuBP
19. As 5 G3P → 3 RuBP, 3 ATP → 3 ADP
20. It takes two G3P to make one glucose
21. Stage labelling: Carbon Fixation, Reduction, Regeneration

Topic 6: Respiration ETC

1. Names of *Complex I, Complex II, Complex III, Complex IV, Q (ubiquinone),* and *Cyt C (Cytochrome C)*
2. NADH gives electrons (e^-) to Complex I
3. FADH2 gives electrons (e^-) to Complex II
4. H^+ come out ATP Synthase to make ATP

5. 1 Glucose will result in 10 NADH, 2 FADH2
6. Complex I transports 4 H^+ across membrane
7. Complex III transports 2 H^+ across membrane
8. Q (or ubiquinone) transports 2 H^+ across membrane
9. Complex IV transports 2 H^+ across membrane
10. Electrons (e^-) travel from Complex I → Q (ubiquinone) → Complex III → Cyt C → Complex IV
11. Electrons (e^-) **also** travel from Complex II → Q (ubiquinone) → Complex III → Cyt C → Complex IV
12. H_2O is made by combining 2 H^+ with Oxygen and the electrons from Complex IV
13. Transport of NADH electrons (e^-) result in a proton gradient of 22 H^+
14. Transport of FADH2 electrons (e^-) result in a proton gradient of 14 H^+
15. A different final electron acceptor can be used in some systems (i.e. anaerobic respiration)

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