Manipulating 3D-Printed and Paper Models Enhances Student Understanding of Viral Replication

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WestEd

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Abstract

Understanding key concepts in molecular biology requires reasoning about molecular processes that are not directly observable and, as such, presents a challenge to students and teachers. We ask whether novel interactive physical models and activities can help students understand key processes in viral replication. Our 3D tangible models are embedded with magnets that accurately represent chemical attractions and, in a study of 492 students, structured model use led to improved understanding of viral replication and self-assembly from pre- to posttest.

Introduction

As technological advances change the field of biology, understanding at the molecular level is essential for a complete understanding of key processes such as protein formation and gene expression. Students learning biology struggle with these concepts, however, as they are not directly observable and visual representations tend to be abstract and complex (Marbach-Ad & Stavy, 2000).

Visualizing and conceptualizing molecular processes presents a challenge to working scientists as well, and 3D physical molecular models are often used to explore spatial relationships between components in ways that are not possible with 2D images alone. For example, physical models were critical in the discovery of the structure of DNA: Watson and Crick manipulated cardboard cutouts of nucleotide bases to determine that base-pair bonding patterns gave rise to the double helical shape of DNA known today (Pray, 2008). Recent technological advances, such as the advent of 3D modeling, has enabled development of more sophisticated molecular models and the proliferation of 3D printers has provided a means for precisely translating 3D representations into physical objects. In this study, we explored how physical molecular models can be used in the classroom to improve student reasoning about molecular biology concepts. We asked whether the 3D and physical models used by working scientists could also be used to scaffold students' understanding of complex concepts that are difficult to observe and to describe using conventional learning materials.

Numerous studies have found that interactions with physical models can improve student reasoning and learning in topics such as human body systems, chemistry, and geology. (Buckley, 2000; Reynolds et al., 2005; Russell & Kozma, 2005). Virology, the study of viruses, plays a crucial role in the high school biology curriculum yet physical models of viruses are essentially non-existent in the classroom. As prolific and ubiquitous agents of many diseases ranging from the common cold to HIV, viruses are present in virtually all people and are frequently the cause of major disease outbreaks such as the recent Zika virus outbreak (Centers for Disease Control and Prevention [CDC], 2016). Studying viruses therefore allows students to draw connections between current events and topics such health and human body systems, the human genome, and molecular processes, while also targeting cross-cutting concepts such as cause and effect, and

structure and function. Given the importance of the study of viruses and the dearth of existing models, we focused on the concept of viral replication, the process in which a virus uses host cell machinery to create many copies of itself, as a case study for the use of novel physical models as educational tools. We examined student performance on distal pre- posttest measures in order to investigate the following questions:

1) Does structured model use lead to measurable gains in student learning?
2) Where are students making the greatest gains in learning?
3) How do differences in teachers' and students' model use influence learning outcomes?

Overview of Molecular Models and Learning Materials

3D Virus Model. We worked with Dr. Art Olson and members of the Molecular Graphics Laboratory at Scripps Research Institute to design and develop an accurate 3D physical model of the poliovirus (Figure 1). The poliovirus structure is composed of identical viral subunits that are critical for replication and self-assembly. The physical rendering, likewise, consists of structurally accurate subunits embedded with magnets. Carefully placed magnets enable the model to represent polar interactions that take place in self-assembly processes. Thus, unlike traditional or static models, our poliovirus model highlights key relationships between structure and function in viral processes.

Figure 1. 3D printed virus model developed by Dr. Art Olson at the Molecular Graphics Lab. Left, Virus pentamers before assembly. Center, Virus pentamers during self-assembly (jar is gently shaken). Right, Fully assembled virus capsid.

Viral Cycle Cards. Dr. David Goodsell of the Scripps Research Institute created complementary paper virus cards (Figure 2), which accurately depict the steps of the viral cycle at the sub-microscopic level. These cards provided another novel representation of the structure of viruses and aid in contextualizing viral self-assembly within the process of viral replication.

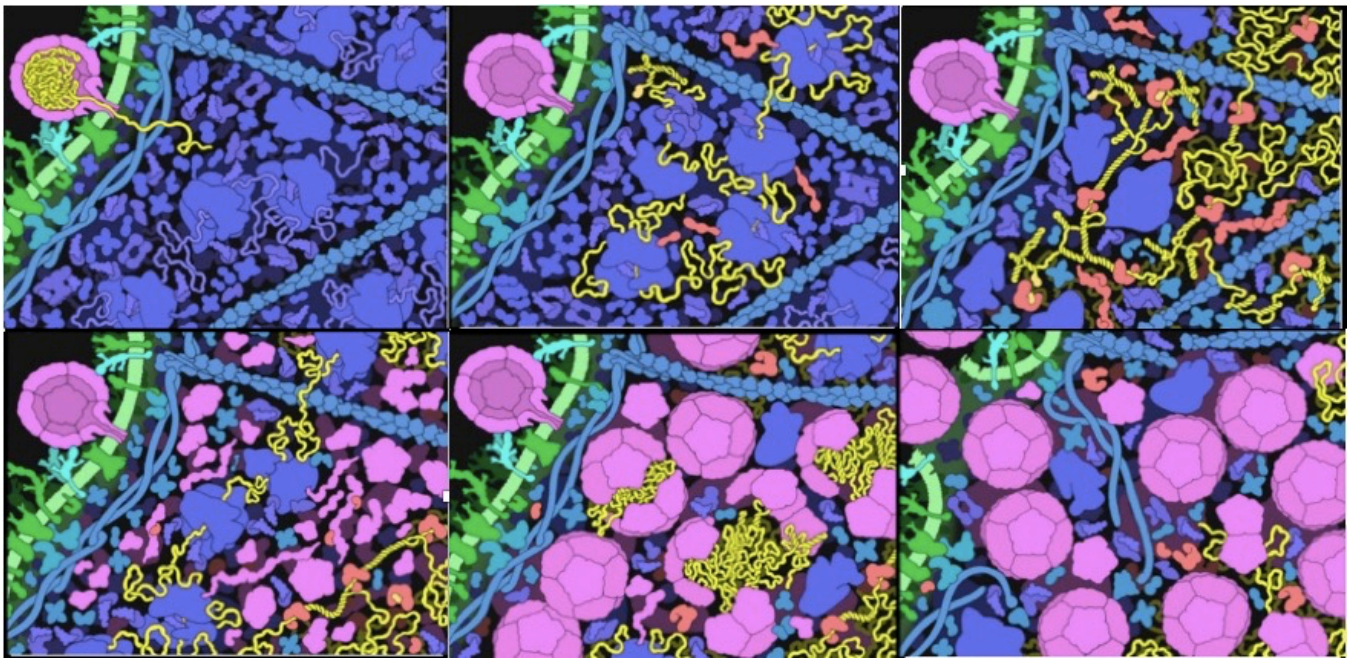


Figure 2. Virus cards developed by Dr. David Goodsell at the Scripps Research Institute

Study Design and Overview of Activities

WestEd researchers designed two days of model-based activities, which were iteratively refined through feedback from select participating teachers. We designed the activities to be used as supplemental instruction during units on viruses, not as a replacement for existing curriculum content. We provided teachers with training on the implementation of the activities and content prior to their classroom sessions.

Each day of the activity included a teacher introduction of the model, small group work with the model, and classroom discussion. The day 1 activity involved students using the virus cards to explore and order the steps of the viral cycle. The day 2 activity involved student manipulation of the 3D-printed virus model to investigate the process of viral self-assembly.

Methods

Participants

The study cohort consisted of 8 teachers across 3 schools in Northern California. In order to be included in the study, participating teachers were required to be teaching two or more

classes of Biology, Biotechnology, or AP biology. These classrooms yielded a total of 492 students who completed all study requirements. The grade-level and demographic breakdowns of the student sample are presented in Figures 3 and 4, respectively. All participating teachers completed 2 3-hour sessions of professional development (PD) with WestEd researchers as part of a series of studies on model use in the classroom. These PD sessions were completed before teachers administered the activities to their students and covered the study background and motivation for developing classroom model activities, key concepts for students to learn through the model-based activities, and data collection responsibilities and timelines.

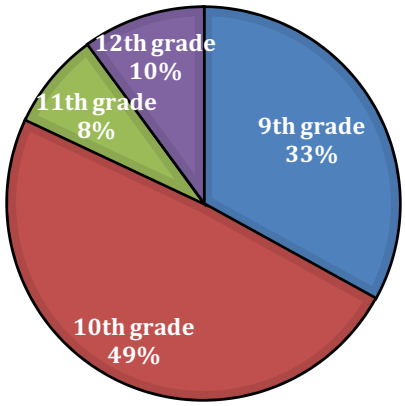
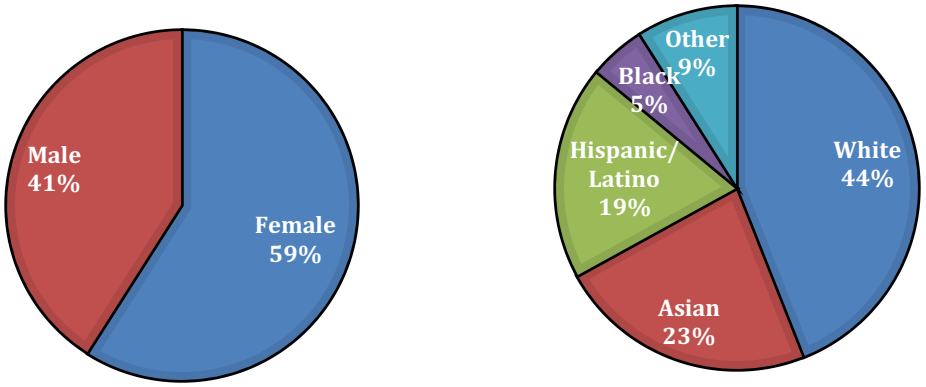


Figure 3. Sample breakdown by grade level



Figures 4. Sample breakdown by gender (left) and ethnicity (right)

Procedure

Activity Sequence. Teachers were instructed to spend two full class periods on the virus lessons, as well as administer a pre and posttest before/after the activities. Teachers were given flexibility in their administration and scaffolding of the activities. The pre- and posttest could occur on the

same day as the lesson or the day before/after. A typical schedule for the activity and test administration is shown in Table 1.

Table 1. Typical sequence of activity and test administration

	Activity/Measure	Time	Data Collected
Day 1	a. Pretest b. Viral cycle activity	a. 10-15 mins b. 30-45 mins	a. Student responses b. Classrooms observations
Day 2	a. Self-assembly activity b. Posttest	a. 30-45 mins b. 10-15 mins	a. Classroom observations b. Student responses

Activities

Day 1 Activity. On day 1, students completed activities related to the steps of the viral cycle using the colored virus cards. The activity began with students reading an article about poliovirus and rhinovirus and discussing the main points of the reading in pairs or as a whole class. Students then worked in small groups to order the six virus cards while discussing the structures present in the cards and the processes occurring at each step. A template with written descriptions of each step of the viral cycle accompanied the cards and was typically used by teachers after student groups had already attempted to order the picture cards as a means to allow students to refine or justify their selections. The activity design included a whole class discussion after group work to review the viral cycle steps and allows students to share how they put the cards in order.

Day 2 Activity. On day 2, students focused on the process of viral self-assembly and involved small groups working with the 3D virus model. Student model manipulation was guided by a worksheet that prompted students to assemble the model from different starting configurations, to dis-assemble the model, and to shake the model at different speeds. Worksheet questions prompted students to consider what was represented by various features of the model, where the energy for assembly comes from, and what factors accelerate the self-assembly process. Group work was proceeded by a whole class discussion reflecting on these questions and on scientific models in general.

Measures

Pre/Posttest. The pretest and posttest were identical assessments consisting of 20 items assessing student knowledge of the viral cycle, viral self-assembly, molecular biology, and scientific models. We made this assessment difficult intentionally in order to avoid ceiling effects, to be sensitive to a range of levels in proficiency, and to motivate complex discussion. A breakdown of the item type and item content is shown in Figure 5.

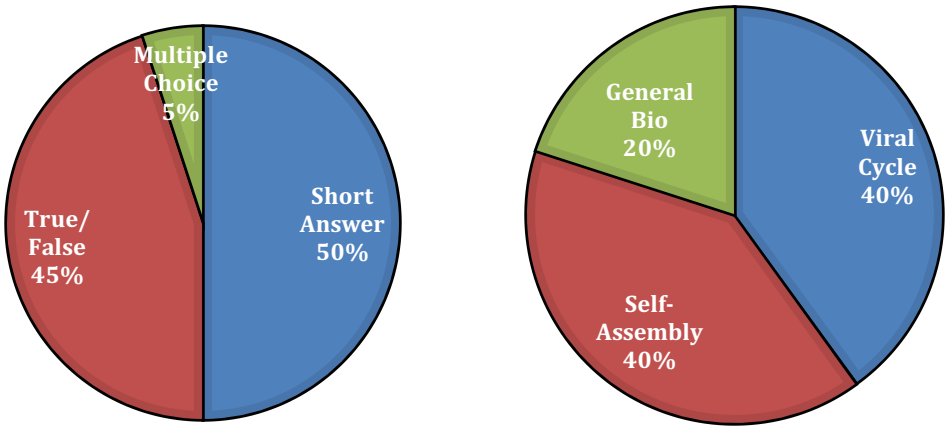


Figure 5. Breakdown of tem type (left) and item content (right) in the 20-item pre/posttest

Classroom Observations. Two trained WestEd researchers observed each day of the virus activities for all teachers. At 5-minute intervals, researchers recorded average values for the observation dimensions displayed in Table 2. Other observational dimensions collected included whole class interaction, group balance, and group interaction, however these dimensions were not included in analysis.

Table 2. Observational variables and values collected by researchers for each day of the activity

Observational Variable	Values
Part of Activity	1. Introduction 2. Small group work 3. Discussion
Model Use	1. All students with hands on model 2. 2-3 students with hands on model 3. 1 student with hands on model 4. No students with hands on model
Teacher Role	1. Teacher not involved 2. Addressing whole class 3. Assisting students systematically 4. Assisting students as needed 5. Monitoring administration

Student and Teacher Reflections. We conducted teacher interviews at the end of the school year to gather teacher input on the models and activities. Specifically, we asked teachers about the feasibility or usability of the activities and models and how the models affected their teaching strategies and their students' learning. Similarly, student attitude surveys were administered after completing all model-based activities. These surveys asked students to reflect on whether or not they found the activities useful and enjoyable, and to provide suggestions for improvements to the models or activities. These teacher and student reflections were not analyzed in detail for this study.

Results

Question 1: Does structured model use lead to measurable gains in student learning?

Figure 7 shows a histogram of student performance on pre and posttest. We carried out a paired-sample t-test on pre and posttest scores to determine whether students make significant learning gains after completing the activities. Students scored an average of 26.7% on the pretest and 43.7% on the posttest, yielding an average learning gain of 17%. T-tests confirmed that this gain was reliable, $t(491) = 20.2$, $p<0.001$. Students showed considerable gains in understanding from pretest to posttest. Next, we explore whether these gains can be attributed to students' and teachers' use of the virus activities and models.

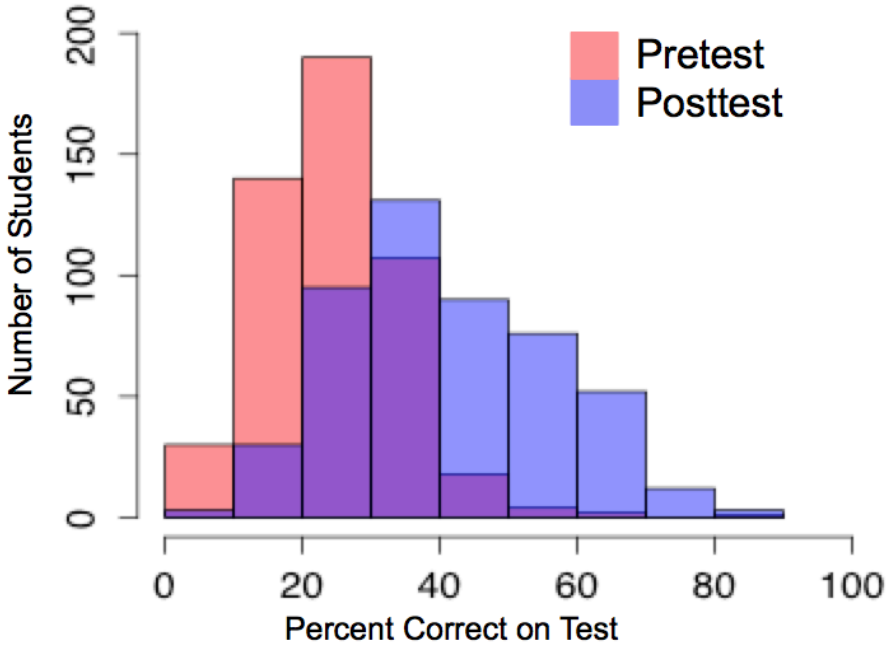


Figure 7. Histograms of student scores on pre and posttest

Question 2: Where are students making the greatest gains in learning?

Figure 8 shows a plot of the number of students answering a given item correctly on the pre and posttest, and Table 3 provides a description of the item. To better understand where students were making the greatest gains in learning, we calculated the differences in the percent of students who answered each item correctly on the pre- and posttest. Separate paired sample t-tests were performed for each item and revealed that students reliably improved between pre and posttest on some items but not others, shown in Table 3.

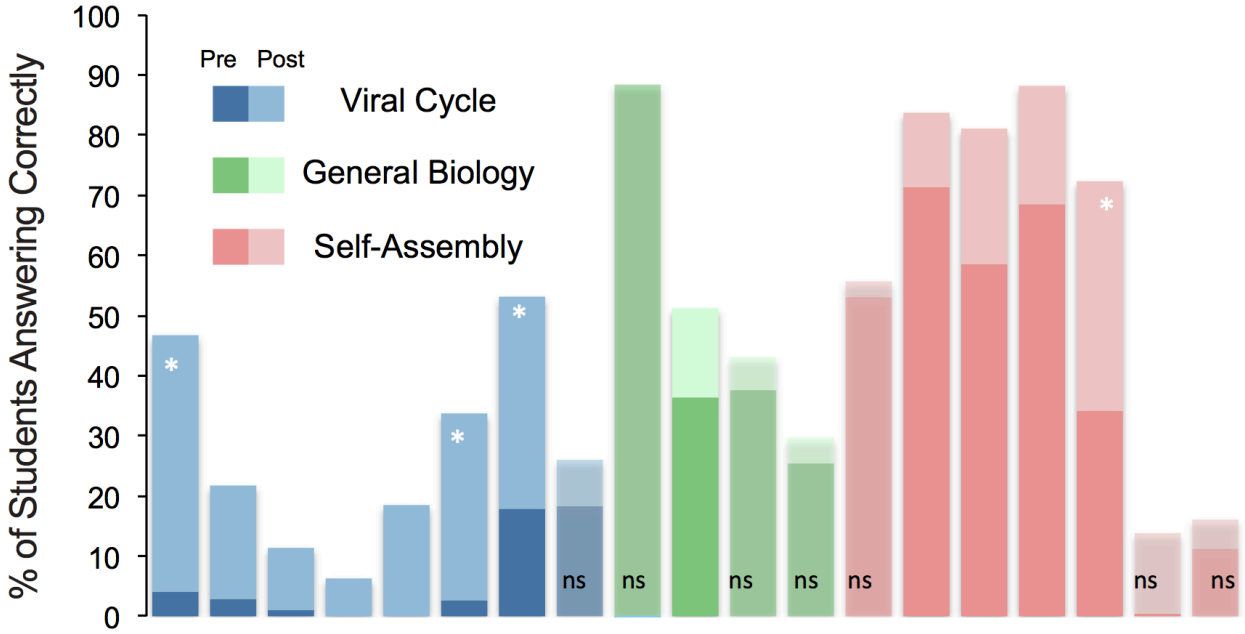


Figure 8. Number of students answering a given item correctly on pre and posttest. Items are grouped into categories (viral cycle, general biology, self-assembly) based on content.
ns: non-significant difference between pre- and posttest.

The largest average improvements between pre and posttest scores were made on items 1a, 1f, 2, and 5e. Items 1a, 1f, and 2 ask students to identify and describe the first step, the last step, and the self-assembly step of the viral cycle, respectively, while Item 5e asks students about "the necessity of random molecular motion for self-assembly". Thus students made the largest gains on the items that were specific to the objectives of the day 1 and day 2 activities.

Table 3. Mean score difference, effect size and t-test results for each item on the pre/posttest

Item	Question text	Mean Difference*	Effect Size** (Cohen's d)	T-test Result
	List and describe the six major steps in the life cycle of the virus			
1a	Step 1	43%	**1.12**	t(491)=17.63, p<0.001
1b	Step 2	19%	**0.60**	t(491) = 9.42, p<0.001
1c	Step 3	10%	**0.44**	t(491) = 6.90, p< 0.001
1d	Step 4	6%	**0.37**	t(491) = 5.75, p< 0.001
1e	Step 5	19%	**0.67**	t(491) = 10.56, p< 0.001
1f	Step 6	31%	**0.88**	t(491) = 13.80, p< 0.001
2	In which step does self-assembly occur?	36%	**0.79**	t(491) = 12.30, p< 0.001
3	Where does a virus get the matter to build copies of itself?	8%	**0.19**	t(491) = 2.93, p< 0.001
	Which of the following can be considered a model of a virus? Circle Yes or No			
4a	A diagram that shows the parts of a virus	-4%	- 0.13	t(491) = -2.03, ns
4b	An object that has the same shape as a virus	15%	**0.30**	t(491) = 4.74, p< 0.001
4c	A sample of a virus collected from an infected organism	5%	0.11	t(491) = 1.76, ns
4d	A photograph of a virus taken through a microscope	4%	0.10	t(491) = 1.50, ns
	Which of the following statements are true about viruses? Circle True or False			
5a	When a virus breaks apart, the parts become new viruses	3%	0.05	t(491) = 0.83, ns
5b	Self-assembly requires energy	12%	**0.30**	t(491) = 4.71, p< 0.001
5c	Attraction between proteins pull them together	23%	**0.51**	t(491) = 7.94, p< 0.001
5d	The viral capsid is made of proteins	20%	**0.49**	t(491) = 7.73, p< 0.001
5e	Viral self-assembly requires random molecular motion	38%	**0.83**	t(491) = 13.00, p< 0.001
	Describe how the factors below affect self-assembly			
6a	The shapes of the parts that self-assemble	13%	**0.54**	t(491) = 8.47, p< 0.001
6b	The energy available for self-assembly	7%	0.10	t(491) = 1.60, ns

* Percent of students answering item incorrectly on pretest and correctly on posttest
** effect size bolded if item improvement was significant at p< 0.001
ns = not significant

Question 3: How do differences in teachers' and students' model use influence learning outcomes?

We explored the relationship between learning gains and teachers' and students' use of the models and activities. In particular, we tested whether differences in gains from pre- to posttest were related to differences in observed dimensions of classroom behavior during the lessons (Figures 9-11). We examined these relationships using mixed-effect regression models with gains from pre- to posttest as predicted values and the three classroom observation dimensions as predictors: teachers' time spent in an engaged teaching role ('Engaged Teaching Role'; Figure 9), students' time spent in hands-on model use ('Hands-on model use'; Figure 10), and the amount of time spent discussing ('Discussion'; Figure 11) the activities. Additionally, we included Item and Student as random effects on the model intercept. Variation in teacher engagement reliably predicted variation in gains from pre- to posttest: test gains were greater for teachers who spent more time actively engaged with students (β=0.31, p<.001). Variation in student model use and lesson structure was also related to differences in test gains: test gains were greater for students who sent more time in actively using the models (β=0.12, p<.01) and for students in classrooms that spent more discussing the models (β=0.16, p<.001). Active teacher involvement, student model use, and discussion time thus account for subtle yet reliable difference in student learning outcomes.

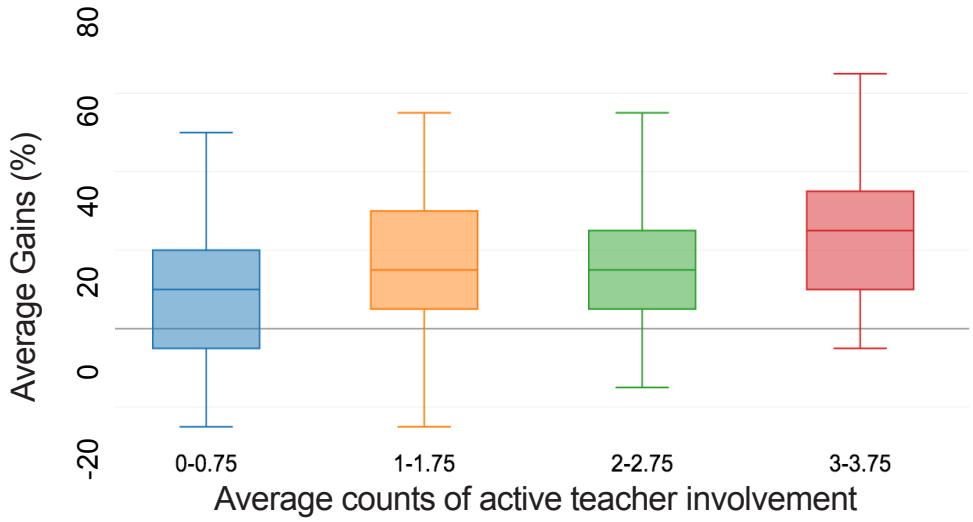


Figure 9. Average gains on pre/posttest scores separated by quartiles of number of observed engaged teaching role instances.

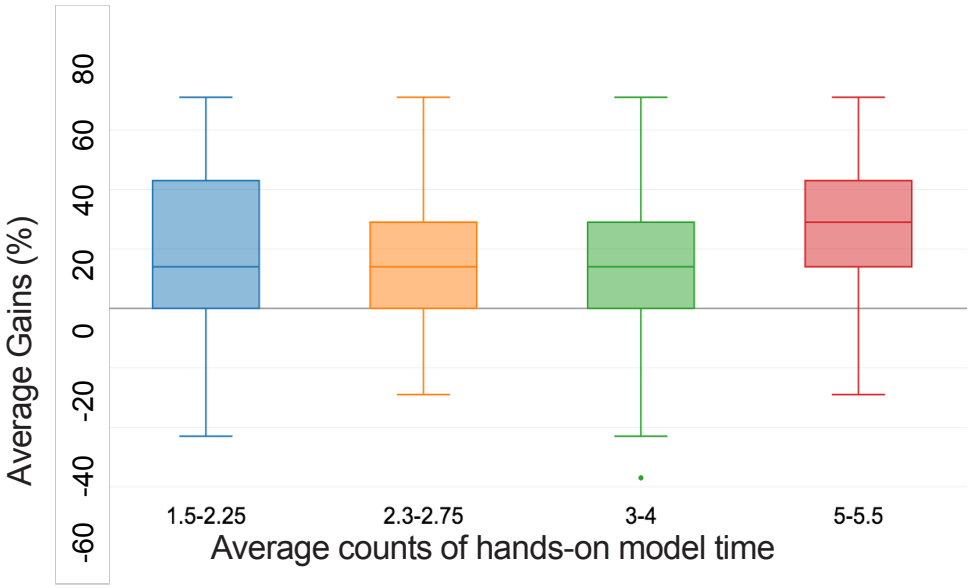


Figure 10. Average gains on pre/posttest scores separated by quartiles of number of observed active model use instances.

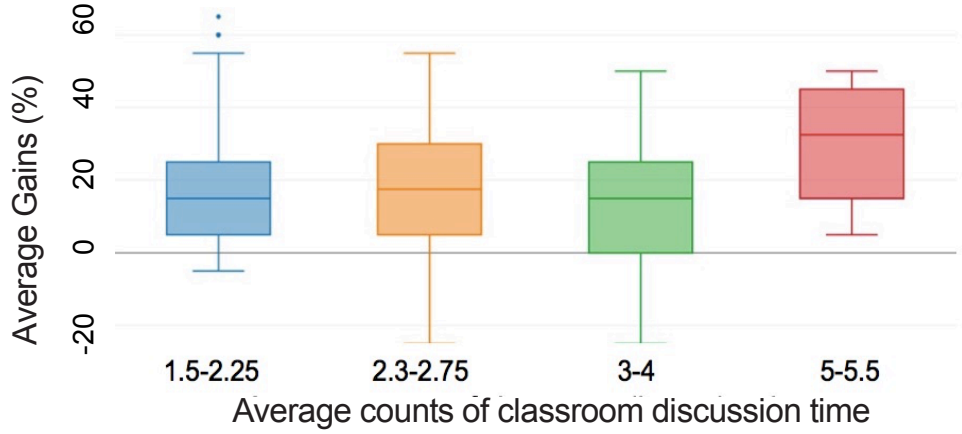


Figure 11. Average gains on pre/posttest scores separated by quartiles of number of observed discussion instances.

Discussion

We demonstrate that the same kinds of physical models used by working scientists can be translated into classroom tools that scaffold students' early learning of complex concepts in molecular biology. Our 3D-printed virus models and cards served as effective tools for learning about the viral cycle and self-assembly, especially when used with activities that support students' interactions with each model. We found that structured virus model use led to measurable learning gains and that these gains were greatest for the concepts that were most closely related

to the objective of the day 1 and day 2 activities. Students made the largest learning gains on questions pertaining to the first and last step of the viral cycle, the self-assembly step, and the necessity of random molecular motion in viral self-assembly. We also found that variation in observable aspects of model and activity use in the classroom was related to gains from pre- to posttest. Specifically, the amount of time teachers spent in an engaged teaching role, the amount of time spent actively using the models, and the amount of time spent on classroom discussion accounted for subtle but reliable differences in student learning outcomes. Students in classrooms with more actively engaged teachers, more hands-on model time, and more discussion time, made larger gains from pre to posttest compared to other classrooms.

The findings suggest that physical virus models can be effective tools for student learning, and that teacher implementation and scaffolding of structured model activities influence student learning outcomes. However, given that active teacher engagement and time spent on modeling and discussion explained a relatively small portion of the variability in student learning outcomes, further work should be conducted to determine what other factors influence students' ability to improve on molecular biology concepts through structured model use. Teacher and student attitudes regarding the utility of modeling likely play a role in student engagement during modeling activities. Teacher interviews and student attitude surveys, such as those collected in this study, as well as observational dimensions capturing the ways in which students engage with the model (i.e. manipulating the model only as instructed, designing their own investigations with the model, playing with the model, etc.) may elucidate this relationship. These data should be collected in a greater number of classrooms to truly explore these complex relationships between teachers, students, and models.

Acknowledgements

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