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Archer Harrold

Allison Cruikshank

Bryan Penas

Rebecca Roston

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Introducing high school biology students to biochemistry with a short, content-oriented module

Archer Harrold[1] | **Allison Cruikshank**[2] | **Bryan Penas**[3] | **Rebecca L. Roston**[2]

[1]Department of Chemistry, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

[2]Department of Biochemistry, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

[3]Science, Lincoln Public Schools, Lincoln, Nebraska, USA

Correspondence
Rebecca L. Roston, Department of Biochemistry, University of Nebraska-Lincoln, Lincoln, NE, USA.
Email: rroston@unl.edu

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Abstract

Many STEM disciplines are underrepresented to High School students. This is problematic as many students' decisions for college are shaped by their experiences and achievements in high school. Short content-oriented modules have been shown to encourage science identity and otherwise benefit the students' learning. Following the ASBMB's outreach protocol, we developed a short content-oriented module aimed at a high school biology classroom. Students interacted with 3D models of DNA and transcription factors while exploring structure–function relationships and introductory biochemistry topics. The high school teacher was impressed with the students' response to the module, specifically the ease with which students learned, their enthusiasm, and their recall of the experience. We provide all materials necessary to use this module, including student worksheet and printable model coordinates. We encourage both high school instructors and professional biochemists to consider similar module using physical models.

KEYWORDS

curriculum design, outreach, protein structure function and action mechanism

1 | INTRODUCTION

High school students' decisions to pursue STEM-related majors in college are often shaped by their experiences and achievements before entering college.[1,2] Unfortunately, there are many STEM majors outside standard high school science classes to which high school students have no exposure (e.g., Microbiology and Immunology, Environmental Science, Biochemistry). A potential solution to introducing additional STEM topics to incoming undergraduate students is utilizing content-oriented, short modules in high school classrooms. Through utilizing content-oriented short modules in high school classrooms students can see higher perceptions of the value of science and improved perception and performance of the desired task or course material.[3] Additionally, content-oriented, short modules can have long term consequences such as impacting students' educational and career choices.[4]

Biochemistry, a diverse STEM discipline with many applications and careers, is not a standard high school subject—relatively little research has been done concerning short scientific learning modules and student outcomes in Biochemistry, however when done in other STEM fields (Robotics, Geospatial Technologies) benefits

Archer Harrold and Allison Cruikshank contributed equally to this study.

including greater self-efficacy, confidence, and cognitive results were found.[3] A more concrete understanding of the impact and outcome of short scientific learning modules in Biochemistry will aid in future development and understanding in the Biochemistry Education Research Community (BECR).[5] Along with the need to further understand learning modules' impact on high school students, the American Society for Biochemistry and Molecular Biology (ASBMB) has emphasized the need for better outreach.[6] Increased availability of short scientific learning modules will positively impact high school instructors and their students.

A major challenge to introducing biochemistry at the high school level is that biochemistry depends on complex biological macromolecules like DNA, RNA, and enzymes. Understanding the relationship between these macromolecules' structure and function was defined as a foundational concept of biochemistry.[7] Using two dimensional representations of macromolecules is popular in teaching due to its accessibility, though it generates multiple misconceptions even in college-level students.[8] Use of three dimensional (3D) graphics (displayed on a two-dimensional screen) is commonly used by researchers and has been employed successfully at the high school level.[9] Use of 3D graphics in teaching requires students to have computing devices. Further, they require a time investment of both instructor and students in learning the software used to visualize the structures. Finally, the few available visualization programs that allow dynamic, interactive visualization of macromolecular interactions are also only meant for researchers and are intimidatingly complex. An alternative strategy is the use of 3D physical models. In contrast, physical models of molecular structures are recognized as low-threshold, high-gain learning tools[10] that can easily be manipulated to show macromolecular interactions. Because this module was designed for a single class period and to demonstrate the importance of structure for macromolecular interactions, we chose to use physical models.

Previous reports in a biology setting found it may be possible to develop science identity at this early level with short term, hands-on scientific learning experiences.[11] Our study used hands-on learning experiences with physical models to teach students about macromolecular interactions in a third-year high school biology classroom. We built our learning goals on ASBMB's foundational concept: Structure and Function, and its associated sub-concepts – "Macromolecular interactions," "Structure and function are related," and "Structure is determined by several factors".[12] The aim of the module was to introduce high school students to complex biochemistry concepts in an engaging manner with meaningful results for all involved. By creating and demonstrating the effect of a short scientific learning module on high school students, other biochemists can use this module directly, or as a scaffold to create future modules.

2 | METHODS

2.1 | Model and module design

The models used in the module represented DNA and transcription factors (Figure 1), these models were previously designed for college-level courses.[13] Model designs, including printable structure files are available for self-printing or modification (DNA, https://digitalcommons.unl.edu/structuralmodels/16/; transcription factor, https://digitalcommons.unl.edu/structuralmodels/20/), and they have been uploaded to commercial vendor Shapeways (www.shapeways.com/shops/macromolecules) for direct ordering. One goal of the module was to make these models useful in multiple contexts, to add value to model ownership. After initial discussions about planning the module, we reached out to the local public school science director who led us to collaborate with a public high school instructor of honors Biology, typically taken in the sophomore or junior year of high school. Through discussions with the instructor, we collaboratively created learning objectives that were congruent with in-class goals and content, and that aligned with ASBMB core concepts for

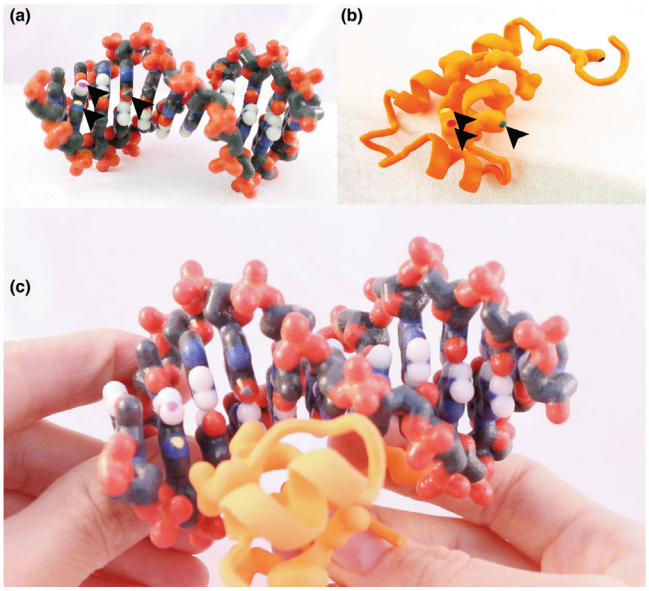

FIGURE 1 3D models used in the module. (a) DNA, (b) Transcription Factor. Students were given both 3D models to interpret structural characteristics and features. Panel c shows students finding biologically accurate binding positions. This was accomplished by matching areas marked with colored dots (black arrowheads in a and b).

Biochemistry. The collaboration approach was consistent with the ASBMB community outreach plans.[6]

2.2 | Lesson overview

The overarching goal of the module was to ensure students discussed each learning goal and allowed time for each student to have hands-on interaction with the 3D models. The high school instructor indicated that student prior knowledge came from life-science instruction in middle school and extracurricular sources. Students had some familiarity with chemical bonds and atoms, and non-molecular familiarity with proteins and nucleic acids. Math knowledge varied from pre-Algebra to Calculus. The layout of the classroom had students sitting at tables in groups of two to four. Each group received one set of models, and each student received their own worksheet (Supplementary Material S1), which they were encouraged to do in their group. There were 26 students in the first, and 25 students in the second class.

All learning objectives were introduced using analogies as leading questions with discussion among the student table groups. Pertaining to our first objective, "What is a molecule and what can it interact with?", we used a familiar analogy to many students, bricks. Students were asked about building materials for a brick wall, and about different structures that can be connected to a brick wall. Brick structure is important for the integrity and purpose of the brick wall and constrains the overall structure of the wall to fit additional structures. Students were explicitly asked to relate this to molecules. Molecular shape is important for the purpose of function and is constrained so that certain interactors can fit the shape. The analogy emphasized the importance of structure to molecules and their interactors. After small-group discussions, the materials needed to build and connect molecules (e.g., atoms and bonds) were discussed as a class. The second objective, "What is DNA?", used blueprints for introducing DNA. Students were given an example blueprint of a house and asked to discuss in small groups, what information it gave them. Small-group volunteer representatives communicated their ideas to the class. We then introduced to students the similarity of blueprints to DNA, using their examples. Post class discussion, students were given a 3D model of DNA (Figure 1). Students were tasked with listing four characteristics and asked, "How might DNA carry the information?" This helped set up the third learning objective, "What is the importance of a transcription factor?" Using the same blueprint used in learning objective two, small groups discussed how big the living room in the blueprint is and how they got this information. This discussion led to the introduction of transcription factors and their role with DNA. The last learning objective, "How does a Transcription Factor help to interpret DNA?", used the brick analogy from learning objective one. Small groups discussed how bricks and blocks mix, and how structures fit together. This question helped lead to the post-small-group introduction of the role that structure plays in molecular interaction.

After the questions on the worksheet were all discussed, students were tasked with a few objectives concerning the 3D models. First, students were tasked with aligning the four marked colored pieces on the transcription factor to the respective marked pieces on the DNA. Students were asked to identify another potential binding site for the transcription factor where all four of the colors on the transcription factor bind to their respective colors on the DNA at the same time. Figure 1a,b show the DNA 3D model and transcription factor 3D model and their binding sites (black arrowheads). After this task, students were told to flip the DNA model to expose the minor groove, then again asked if they could find a binding site on the minor groove. Instructions were given to aid this process.

The created lesson plan fit well with the instructor's initial syllabus for the class, which typically covers proteins and nucleic acids after the time of the module. This means all information covering transcription of DNA, and all molecular details of DNA and proteins was new during the module.

2.3 | Data collection and analysis

Students were given a post-module survey that included six general knowledge questions over molecular composition, molecular connections, and interactions between molecules. Because of the classroom arrangement, students were able to consult their group during the survey, though each student was requested to complete their own, some students turned in a single survey with multiple names. One student left class before the worksheet for reasons unrelated to class content. Twenty-five total worksheets were received.

Student responses were scored based on a three-point rubric for each question (Table 1). This data was then averaged and analyzed using excel, to identify answer trends.

To understand if the module engaged the students and was meaningful for them and the high school instructor, the high school instructor was interviewed the following school year in the fall.

TABLE 1 The rubric indicates score assigned students for a completely correct answer (3), a partially correct answer (2), and an incorrect answer (1). (Average student score (S) and Bloom's Taxonomy level (B) of questions are indicated.

	3	2	1	S	B
What is a molecule made of?	Mention of Atoms/DNA/ Protein	DNA and Proteins	Mention none of the above	2.8	Recall
How are they connected?	Includes bonds (complete)	Describes connection (partial)	Mention none of the above	2.7	Recall
What allows different molecules to interact?	Shapes/Spacing and Molecules	Transcription Factor/ Protein/Stating connection	Mention none of the above	2.4	Recall
What information does DNA carry?	Instructions for cells/ Genetic makeup/ Instructions for you/Blueprint	Characteristics (e.g., stating hair, eye color)	Outstanding information unrelated to characteristics/info	2.6	Recall
What is the role of the transcription factor?	Reads DNA/Allows cells to work/Binding	Connections/Proteins	Mention none of the above	2.5	Recall
How does the transcription factor interpret DNA? What allows this?	Interacts with DNA by Reading/Binding/ Scanning	Mention of Proteins/ Interaction with Proteins	Mention none of the above	2.6	Analyze

3 | RESULTS AND DISCUSSION

Questions one through five were oriented toward information covered in each learning objective. In an interview done with the high school instructor in a post module, he mentioned that he believed questions 2 and 3 to be recall questions of information students should have knowledge over, while questions 1, 4, and 5 would be recall from the activity. Question six dealt with a more complex idea, "How does the transcription factor interact with DNA? What allows this?" and this would be slotted between the understand and analyze tier of bloom's hierarchy. Students must be able to understand the taught concepts (transcription factors and DNA) and connect the knowledge from molecular interaction to answer this question. This is more complex than recalling information and requires students to analyze potential solution paths for their answer.

Questions one through five generally scored very high on average and were considered recall questions. The lowest average score being 2.4 out of all six questions. This means students were able to recall information at a very high rate—most of the questions asked could be seen in the activity word for word, or close to it. Specifically, questions one and two had the highest average scores where 80% and 76% students were scored a level three, respectfully. These two questions dealt with molecules and bonds, and according to the teacher these students were taught prior to the module about these concepts. This correlates to the high scores in reteaching these during the session, and having prior knowledge led to the highest scores out of the questions. Questions three, four, and five all had on average lower scores but still were overwhelmingly positive (many level three students). These concepts were introduced to students for the first time in these class sessions, and the scores reflect that students had very little trouble recalling this information taught.

Question six had one of the higher averages at 2.6 despite being the most complex question. Student responses included talking about interactions with DNA.

For the impact of the module, the instructor was interviewed for his thoughts. They mention:

> "there is evidence here that, and from my experience, when students interact with something in their hands they are going to have better retention and it will make a really abstract concept more concrete for them which is really important for freshman and sophomore [students]."

When asked about implementation into classrooms they responded:

> "Yes definitely, I can see this level or something all the way up to AP (Advanced Placement) or down to the shape of enzymes. Something like this in several locations. Thinking of it like a wall and breaking down that wall with one classroom activity just looking at the data."

Biology has a large amount of material—any short-term module that can help students interpret and learn pieces of information should be welcomed. The instructor also related that the students had "fast takeaways" of big chunks of information for a standalone lesson which meant that students were engaged and paying attention. Concluding his thoughts on the module:

> "What I am seeing looks really good, the investment of time, which is always an issue in biology classrooms, its effective and worth considering doing again in the future."

From the perspective of the researchers, it was an absolute pleasure to interact both with the high school instructor and the high school students using the models. Because the models are small, plastic, and brightly colored, initial reactions to them tend to mimic reactions to toys. This was amplified in the students, which even vocalized expressions of interest when handling the models. The high school instructor made sure that the class expected the interruption to their normal schedule, and the students were relatively gracious in their level of participation. Students volunteered answers when asked, and the small-group format made sure that non-participating groups could easily be called on without singling out any students. The defined format of the interaction, including a worksheet to continue progress was advantageous from the perspective of keeping students and the lesson focused. It also allowed high-performing groups to consider the next question during group consideration times, instead of losing attention to other activities. Overall, several aspects of the module were key: (1) reaching out to the high school instructor during development of the activity to ensure its utility in their classroom, (2) interactive, touchable items, for example, models, (3) a group-based worksheet interspersed with instructor and large-group interactions.

As mentioned in the introduction, High school students' decisions to pursue STEM-related majors in college are often shaped by their experiences and achievements before entering college. It is clear introducing stem topics to incoming undergraduate students helps shape future experiences.[1] Introducing Biochemistry topics that synthesize with in-class material in high school biology classrooms can help aid students understanding of difficult biology information and help introduce students to additional STEM topics in the discipline. By utilizing a content-oriented, short module in a high school biology classroom, students recalled multiple levels of structure–function relationships between DNA and transcription factors, displayed themes of active engagement, quick takeaways, and gained knowledge in a foundational biochemistry topic. These results should not be overinterpreted as the data set is small, and students' gain will likely vary with their background knowledge which is driven by local curriculum standards. It is our hope that this study will serve as a model on which STEM university faculty can generate content-oriented short modules with high-school instructors in the future.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Rebecca L. Roston https://orcid.org/0000-0002-3063-5002

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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