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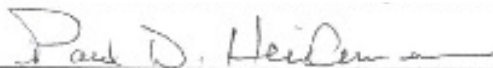
Sketching to Learn in High School Biology Classrooms

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science in Biology from
The College of William and Mary

by

Emma Robin Arents

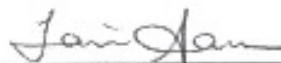
Accepted for Honors



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Abstract

This pilot study tested the ability of the materials we created to elicit higher-order understanding and model-based reasoning (MBR) at three high schools. Participants completed iterative review sessions for an introductory biology topic, either through sketching or reading a text outline. After iterative review, participants responded to a single-question assessment. The question involved transfer of the information provided to students. The structure-behavior-function (SBF) coding structure used to analyze student answers distinguished levels of understanding in student responses (descriptive, explanatory, or integrative). However, grading written text responses alone did not provide adequate information to determine whether the student participants utilized MBR in developing their response. A later pilot or full study will utilize revised materials to continue to assess potential applications of sketching.

Introduction

Of the academic departments and majors open to incoming college freshmen, STEM disciplines face the highest rate of turnover. This problem has endured for decades; still today many high school graduates find themselves feeling underprepared or overwhelmed in undergraduate science classrooms (AAAS & NSF, 2011; Chen & Soldner, 2013; Rodrigo-Peirís et al., 2018; Austin, 2018). High school science teachers need instructional methods that better prepare their students for the higher cognitive demands they will experience in early college courses. Improving system-level (SL) understanding and model-based reasoning (MBR) may improve the outcomes of next-generation undergraduates within STEM disciplines.

SL understanding has become critical for the teaching and learning of content within the natural and social sciences. SL understanding will be necessary for students to access in the context of global challenges (Yoon & Hmelo-Silver 2017). In biology classrooms in particular, complex systems are becoming increasingly central to learning and are frequently highlighted in curriculum standards at both the national and state levels (National Academies of Science, Engineering and Medicine, 2013; VA Department of Education, 2018). Teaching SL understanding in science classrooms will increase the likelihood that students develop a deeper understanding of content (Sabelli, 2006; Smith et al., 2013; Yoon & Hmelo-Silver, 2017).

For educators, teaching SL understanding carries several immediate challenges. The amount of literature on teaching strategies for SL understanding can be overwhelming (Dunlosky et al., 2013; Yoon & Hmelo-Silver, 2017; Science Education Partnership and Assessment Lab, <http://www.sfsusepal.org/>). As teachers sift through the available articles, they are likely to come across multiple outcome measures for each intervention as well (Hmelo-Silver & Azevedo, 2009; Dunlosky et al., 2013; Smith et al., 2013). Some of the best measures are direct, in that

they measure student performance after an intervention. But many are indirect, in which researchers rely on students' opinions and self-reported data (Prince, 2004). If a large effect size is discovered through indirect methods, the result may be less reliable. A smaller effect size based on direct metrics could be just as powerful for learning as a larger effect size from indirect measures, primarily because direct and more objective measures specifically address student understanding.

A promising approach for direct measurement of SL understanding is structure-behavior-function coding (Hmelo-Silver & Pfeffer, 2004). The structure-behavior-function (SBF) coding scheme requires a principal investigator and an independent research assistant. Both parties analyze participant problem-solving interviews to code student work across three axes; core content (components and structure), understanding of component mechanisms (behavior), and description of system interactions and patterns (function). The structural axis includes the components of a system as well as their basic characteristics; the knowledge generated along the structural axis is often foundational. The behavioral axis involves the knowledge of how the structures act in the system. The functional axis is the highest level of SL understanding, and involves the understanding of how components interact and implicit patterns in interactions between components (Yoon & Hmelo-Silver 2017, Bar-Yam 2016). In breaking understanding into the three primary axes of structure, behavior and function, analysis of SL understanding becomes more objective. SBF coding affords teachers greater opportunity to assess student understanding of content after it has been covered. As a result, educators are provided an opportunity to respond to and perhaps enhance students' higher-order thinking skills.

Higher-order thinking skills are known to improve under active learning conditions; these allow students to move beyond structural or descriptive-level thinking into explanatory and

integrative cognition (Grabinger and Dunlap, 1995). Active learning is defined in many ways within the landscape of education literature, though some elements are present in most definitions. Most active learning definitions emphasize student engagement in the learning process, during which self-reflective activities are utilized (Grabinger & Dunlap, 1995; Prince, 2004). Drawing and sketching are particularly promising active learning methods because they meet all criteria emphasized.

Drawings and sketches are visual representations that can illuminate multiple levels of student understanding, including structural components, relationships, or entire processes. Sketches as study aids are also known to improve understanding, reasoning, and problem-solving skills (Ainsworth et al., 2011; Dunlosky et al., 2013; Heideman et al., 2017). Drawing is also a useful communicative and cognitive tool (Quillin and Thomas, 2015). Sketching can initiate an internal dialogue in the mind of the student and provide an “externalization of mental imagery” (Thurlow & Ford, 2018). Sketching also facilitates MBR in biology undergraduates, which is critical in the development of SL understanding (Heideman et al, 2017; Hauge, 2018; Thurlow & Ford, 2018; Hauge, Arents and Heideman, unpublished data). As a result, drawing and sketching can encourage greater recall and understanding by undergraduate biology students (Bilda & Gero, 2005; Ainsworth et al. 2011, Quillin and Thomas 2015; Heideman et al. 2017; Thurlow & Ford, 2018).

This thesis aims to develop and assess materials to identify the instructional utility of sketching on a broader scale. If sketching and the development of MBR can enhance SL understanding in high school classrooms, then high school students will be more capable of meeting changing standards and global challenges. Here, we present materials and pilot data to

suggest ways to apply sketching models effectively to foster SL understanding in high school students.

Theoretical Framework

This project is built on several themes: Mayer's principles of multimedia learning, the distinction between mental models and MBR, and the components of abstract drawings and sketch instruction. Each theme has been supported in the literature, but needs to be made explicit here in terms of its use within our research. All of these concepts will be integrated in an example in a later section of the theoretical framework.

1. Mayer's Principles of Multimedia Learning

The sketching methodology used in this research is a form of multimedia learning (MML). MML is a framework for teaching that presents information to the learner in both verbal and pictorial formats according to a series of principles. The assumptions about learners' cognitive processes from MML theorists are in direct opposition to another learning model termed information-delivery theory. Information-delivery theory is retention-based, suggesting that students are merely vessels for information provided by the instructor. MML applies an alternative, knowledge construction theory, which emphasizes the importance not only of the selection of critical information but the organization of this information into mental structures. During the process of knowledge construction, these structures are integrated with one another and with prior knowledge (Figure 1) to develop understanding (Mayer, 2009). Organization and integration of information is crucial because transfer situations require students to do more than merely retrieve information (Van Meter & Garner, 2005; Mayer, 2009). In an example of multimodal lesson design, information-delivery theorists would argue that all images and text should be presented in their full form regardless of placement, while knowledge constructivists

would posit that learners will gain deeper understanding if the lesson designer 1.) simplifies the verbal information presented by distilling it to its most important characteristics (coherence principle) and 2.) places it directly next to its associated image (spatial contiguity principle).

The principles of multimedia learning are based on three assumptions about cognitive processing (Mayer 2009). The first two relate to sensory processing: (1) humans receive information through distinct auditory and visual channels, and (2) both of these channels have a limited capacity. Multimedia design takes both into consideration by suggesting the use of narration with an image as opposed to printed text. The combination of image and printed text relies on the visual channel alone to process both pieces of information; this combination applies an increased load on the channel and may hinder learning. With an image and narration, both the auditory and visual channels are used simultaneously to reduce the strain on the visual channel (Figure 1). The third assumption is that meaningful learning requires active selection, organization, and integration of incoming information (Mayer, 2009; Schuler et al., 2014), both visual and auditory (Mayer, 2009).

Mayer organizes his principles by three goals (Mayer, 2009; Table 1). The first goal is to reduce extraneous cognitive load by minimizing processing demands of non-instructional content. The second goal is effective management of essential cognitive processing. Although this processing type is essential for learning to occur, requiring too much essential processing exceeds a learner's cognitive capacity. As a result, this overload severely limits the learner's ability to make connections between verbal and visual bases and integrate these effectively. The processing required to make these connections is the final goal of Mayer's research, termed generative processing (Mayer, 2009). Generative processing is required for learning because it is strictly devoted to making sense of essential material.

MML Principles	Definition and Theory	Goal
Coherence	Delete all extraneous information from the presentation of the lesson	(1) Reduction of Extraneous Load
Signaling	Highlight the essential words or graphics when it is impossible to remove extraneous information through the coherence principle	
Redundancy	Delete redundant captions from the narration of a lesson	
Spatial Contiguity	Verbal information should be placed near the visual component to which it corresponds	
Temporal Contiguity	Verbal and visual information should be presented simultaneously to increase the likelihood for students to build connections	
Segmenting	Present a lesson in parts that are user-paced as opposed to a continuous lesson	(2) Management of Essential Processing
Pre-Training	Before the lesson, train students by providing the name and basic characteristics of key components	
Modality	Verbal and visual information should be given in the form of narration and images, rather than printed text and images	
Multimedia	Presenting words in addition to pictures will often facilitate deeper learning rather than words or narration alone.	(3) Fostering Generative Learning
Personalization	Narration in a conversational as opposed to formal tone, or directing comments to the learner, may provide social cues to an otherwise impersonal lesson	
Voice	Using a human voice as opposed to a computer-generated voice may enhance deeper learning by increasing the social aspect of a multimedia lesson	
Image	Having a picture of the narrator on the screen may reduce deeper learning. Very little support and a small effect size for including an image of the narrator; more research is needed	

Table 1. Mayer's Twelve Principles of Multimedia Learning (2009).

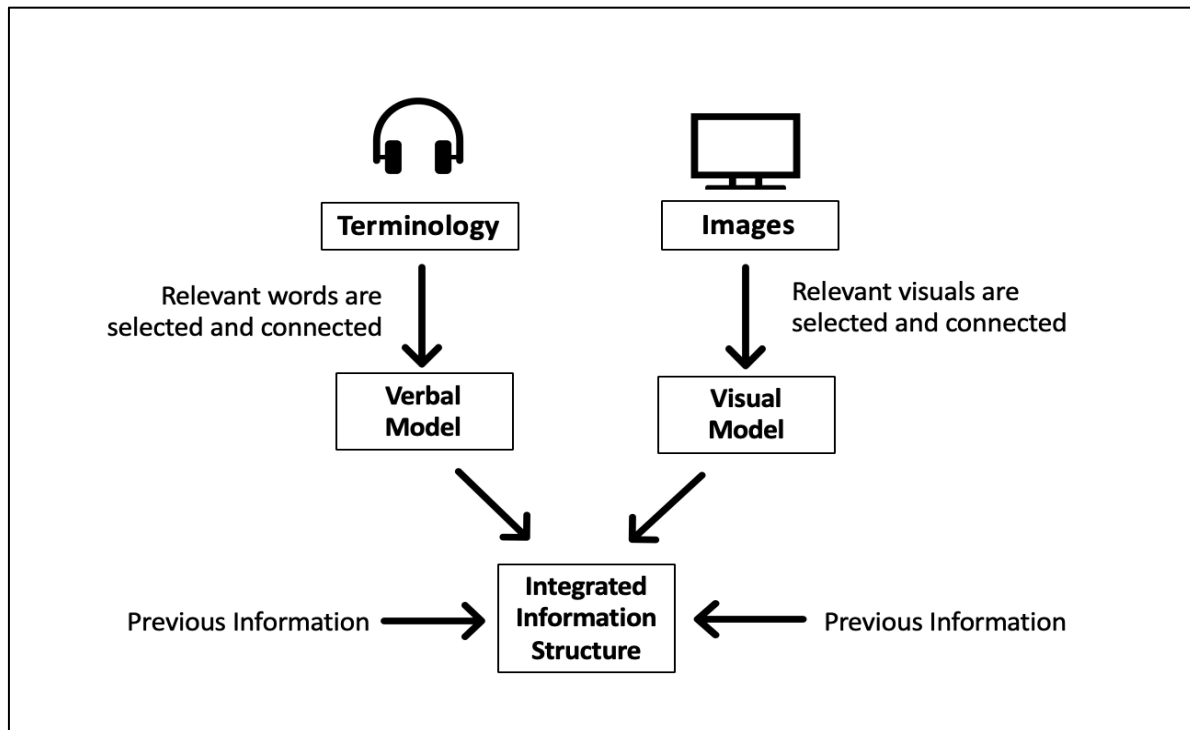


Figure 1. Procedural steps of multimedia learning theory used by students to select, organize and integrate information into a single structure.

2. Model-Based Reasoning (MBR)

Analogical models (hereafter referred to as “models”) are tools available to students to reduce cognitive load and thereby improve learning efficiency. Models are used to depict hard to observe or non-observable systems and processes by representing them in abstract ways. The term ‘abstract’ is used here because while models encourage student understanding, they are not “one-to-one” reflections of the system described (Harrison & Treagust, 1998; 2000). Models impact understanding nonetheless, primarily by requiring students to select important information and organize it into cognitive frameworks (Mayer, 2009). Models have been classified as powerful tools for conceptual change in the literature, but several clarifications should be made regarding their use in model-based reasoning (MBR).

First, a mental model is not automatically synonymous to a mental image. If a student is able to produce a mental image, that means they can close their eyes and retrieve an image or diagram, including its notable surface features. A model, by contrast, is able to be manipulated. Manipulation is prompted by transfer problems, which often describe a shift in environmental conditions. A transfer problem may tell students that the sodium ion concentration available in the extracellular fluid is lower than normal, and asks students to develop a logical response occurring at the cell membrane. A student with a mental image of plasma membrane permeability would not be able to use the visual as a model to work through likely responses. They may be able to close their eyes and “see” fewer sodium ions in the extracellular space, but ion channels and pumps on the membrane would remain stagnant. With a mental model, they might envision a mutation in the regulatory region of a sodium channel gene to increase transcription and thus the number of available channels, thereby increasing the likelihood of sodium contacting ion channels. Explanatory and integrative knowledge of the plasma membrane are invoked as a result. In the literature, the manipulation skill needed to model possible causes or responses related to altered environmental conditions such as reduced availability of sodium ions is called “procedural thinking” (Harrison & Treagust, 2000). Thus, mental images must be adjusted if they are to double as mental models (Cooper et al., 2017).

MBR is also heavily dependent on visual literacy skills (Quillin & Thomas, 2015), the ability to understand and use the conventional symbols used in the abstraction of a structure or process of interest. In other words, recognizing and understanding these conventional symbols facilitates MBR. To develop these skills, students often rely on their instructors or computerized sketching tools for examples of model production (Heijnes et al., 2017). If students do not understand the procedural steps in the creation of a pliable sketch or diagram, they are unlikely

to recognize the analogies between the model and the content it exhibits. By observing the creation of a model, students are able to recognize the transition from verbal to visual information while growing accustomed to conventional symbols and abstract representation strategies (Quillin & Thomas, 2015). As students internalize these techniques, space opens in working memory to devote not just to model creation, but its application to solve problems. Generating and using a model to solve problems is challenging for students at all levels unless teachers devote classroom time to MBR (Van Meter & Garner, 2005). Efforts to develop MBR skills in students may co-occur with instruction if educators integrate models in their lessons. Teaching content and teaching MBR skills are not mutually exclusive.

Taking advantage of models prompts students to move beyond novice-level understanding, towards conceptualizing the deeper characteristics of a system. Moving past surface features that are the primary focus of novices or low-level modelers (Harrison & Treagust, 2000; Jee et al., 2013) facilitates student development of problem-solving ability and expertise (Smith et al., 2013; Quillin & Thomas, 2015). Engagement with deeper characteristics can also develop connections between models, which is an important skill to reason through difficult problems requiring nuanced understanding of a system.

3. Abstract Drawings and Sketches

Our project emphasizes abstract drawings. Drawings are characterized in the literature by their level of realism; a representational drawing is highly realistic, while an abstract drawing uses symbols and is not strictly true to form (Quillin & Thomas, 2015). A representational drawing by a student may show the field of view seen under a microscope. An abstract drawing may focus on the plasma membrane of one of these cells, which may be depicted as two curved, parallel lines. Abstract drawings by students are often applied for simplification of images in a

textbook. Despite their simplified form, abstract drawings nonetheless carry meaning, and perhaps even more meaning, to assist students in meeting learning objectives.

Three learning objectives for abstract drawings suggested in the literature are directly applicable to this project: (1) the construction of a mental model, (2) development of content knowledge, and (3) enhancement of problem-solving skills (Quillin & Thomas, 2015). The nature of the first objective was described earlier. The latter two objectives, content knowledge and problem-solving, are, respectively, lower-order and higher-order cognitive skills (Anderson & Krathwohl, 2001).

The development and assessment of content knowledge is critical in classrooms for obvious reasons; high-stakes tests assess school progress and educational value using student pass rates and test scores (Spring, 2018). Students' test scores primarily hinge upon their comprehension of state-standardized content that is largely recall-based (Spring, 2018). The content knowledge required by these tests might only require lower-order cognitive skills that do not encourage high school students to develop SL understanding.

Take the circulatory system as an example: the ability to recognize structures such as the chambers of the heart is heavily emphasized in high school biology courses. Recognition that allows descriptive labeling of structures will not provide information about how these chambers circulate the blood. Recognition may be supplemented by explanation of the function of each chamber and associated valves. While knowledge of mechanics improves understanding, most students would still find it difficult to describe how the system operates as an integrated unit. To demonstrate SL understanding, students must develop higher-order problem-solving skills. For example, a question for the circulatory system that requires SL understanding tells students a valve is dysfunctional and asks them to predict the response of the heart and the speed at which

blood circulates. In providing an answer, students must integrate descriptions and explanations; being able to label the structures and list their functions is not enough.

Without connections between the functions of each component, students may not conceptualize how a change in one structure affects another. For a student lacking an integrated concept of the circulatory system components and functions, a dysfunctional valve may affect the outflow of blood from one chamber without affecting the inflow of blood to the second. This is an integral misconception that denotes an absence of SL understanding. While knowledge of the structure and function for each system component may engender student success on state-standardized assessments, students are left largely unaware of the impact the mechanics of the system have on its ability to work.

4. Integrative Example for the Theoretical Framework: Incorporation of Sketching Pedagogy in an Undergraduate Classroom

In a recent study at the College of William and Mary, the impacts of sketching were measured in undergraduate classrooms (Hauge Honors Thesis, 2018; additional unpublished data from Hauge, Arents and Heideman, 2018). MBR skills were developed when abstract drawing techniques were incorporated into the Integrative Biology of Animals (IBA) course; an intermediate-level course taken after two semesters of General Biology. Students in the course used sketches in homework assignments, during lectures, and in answering exam problems.

Homework

IBA material was introduced in homework assignments preceding course lecture sessions. The sources made available for students' sketches varied; some would involve watching a narrated sketch video on YouTube, while others involved referencing assigned textbook figures or an internet source. Narrated videos applied multimedia principles (Mayer, 2009; Table 1) to foster learning. Sketches that referenced the textbook or internet sources

invoked the coherence principle (Mayer, 2009; Table 1), and were used to simplify a complex figure to reduce extraneous load. By assigning more basic material before class lectures, the professor allowed more time during lecture to be used to sketch full systems and processes. By incorporation of the pre-training principle (Mayer, 2009; Table 1), more time could be devoted to connection-building and applications of knowledge during lecture (Moravec et al., 2010).

Lecture

In class lectures, the professor made sketches on an iPad connected to the classroom projector. While he drew, the professor would also narrate how he chose to represent dynamic structures and systems. This instructional method reduced students' extraneous load using the temporal contiguity principle, managed essential processing using the modality principle, and encouraged generative learning using the multimedia principle (Mayer, 2009; see Table 1).

Students would often follow along during lecture sessions by drawing the sketches in their notes as the professor drew them during class. The sketches were abstract and were intentionally designed to be easy to reproduce; advanced drawing skills such as perspective were deemphasized to reduce student sketch inhibition (Booth et al., 2014). In fact, the professor often urged the students to further simplify their sketches as they grew more familiar with representing complex systems. By explaining how students could simplify sketches, the professor encouraged students to develop visual literacy (Quillin & Thomas, 2015). Simplifying sketches could also save time without sacrificing content. For example, if a student had developed an understanding of the structure of the plasma membrane, repetition of the double layer of hydrophobic heads and hydrophilic tails would not contribute to their understanding of the system even if these were abstract in form. Recognizing this, the professor encouraged shorthand in all sketches. Some shorthand techniques, like the use of two parallel lines

representing a plasma membrane, were explicitly stated as conventions; others were left to student discretion based on self-assessed understanding.

Exams

Drawings and sketches were encouraged on the IBA exams. The free-response questions relied on transfer; they required not only system recall, but predictions of how that system would respond to a given change. Students with a mental image would be able to reproduce the surface features of the system, and often reproduced a sketch from lecture. While correct under normal conditions, this representation was not a sufficient answer. Students with a mental model would be able to manipulate the system and predict the response, thereby exhibiting MBR skills. The mental model was often described by a sketch that showed these manipulations and how the system would respond. This answer would receive full credit as long as the manipulations made logical sense according to the model's normal function.

Methods

The research question addressed in this project asked whether introductory high school biology students have greater recall, understanding, and model-based reasoning (MBR) skills after using and practicing sketches as part of content delivery. To answer this question, participants complemented classroom material for two introductory biology topics with sketching video walkthroughs or text outlines (Protocol PHSC-2018-08-24-13115-pdheid). Participants' recall, understanding, and problem-solving ability for the topics were compared between two groups of participating students in a biology classroom at three different sites. This research focused primarily on the development of materials to meet this end.

Participants:

Participants were high school students in one of three introductory biology classrooms. All three sites were located in Virginia; one was a county school (S1), and the other two were magnet schools (S2 and S3). One of these magnet schools offered a full-day program (S2), while the other offered half-day programs (S3). There was no enrollment number requirement for sites to partake in the research. At each site, characteristics such as grade level, age, and gender did not exclude any student from participating as long as they were officially enrolled in the course.

In each classroom, participating students began with a five to ten-minute preliminary online survey. This survey primarily measured the study methods utilized by participants before the data collection period. Students first selected study methods they used from a list that included both passive and active techniques. The embedded question logic allowed students to estimate their approximate percentage of study time spent on each method selected. For significance analysis, the false discovery rate was set at 5%. The survey also produced a unique study code that was used as an identifier for participants throughout the intervention. While all students were given the opportunity to take the survey and create a study code, only those who had turned in parental consent and student assent forms were permitted to move forward to the data collection phase.

Data Collection:

Prior to any intervention activity, all participants received a copy of the study instructions (see Appendix A). For each participating classroom, two topics of approximately equivalent difficulty were selected from the Virginia Standards of Learning (VA-SOL) guidelines (Virginia Department of Education, 2018). The topics were site-specific, in that their selection was based on the classroom instructors' pacing and time available (Table 2). For this reason, there was no

topic overlap across the three sites, but this allowed researchers to develop a larger materials library.

Site	Topic 1	Topic 2
1	<p>Protein Channels Link: https://youtu.be/Vm6OMNxowrY</p>	<p>Enzyme Function Link: https://youtu.be/VdN9KzmqDRY</p>
2	<p>Cell Scaling and Allometry Link: https://youtu.be/pTqn1FWuCCE</p>	<p>Cell Cycle Checkpoints Link: https://youtu.be/m6fiOdAzzas</p>
3	<p>The Hydrophobic Effect Link: https://youtu.be/u-TrlfqFfdc</p>	TBD

Table 2. Selected topics by site; below each topic is the link to its narrated sketch video.

For S1 and S2, a video was prepared for each topic. The videos included a narration of a sketch as it was being drawn. Each sketch encompassed all primary components of the system described and was structured to be reproducible within 60 seconds. A written outline was also created for each topic that included the same components. For the first topic (Topic A), one group of participants (Group A) received the link required to view the video, and the other group (Group B) received the text outline. For the second topic (Topic B) the groups' roles were reversed; Group B received the video link while Group A was given the text outline. The groups were selected by the classroom instructor and were equal or nearly equal in size. All participants studied both topics; the only difference was the study method used. Over the course of the intervention, the classroom instructor followed their typical approach to the content, and participants were allowed to supplement their studying of the topics with additional methods they were accustomed to using.

The sketching group received access to the sketching video through a link provided by their instructor via e-mail. The group was instructed to practice the sketches with relevant

keywords at least three times on three different days before the assessment. Sketch instructions explained that the quality of the sketches may be of any degree, as long as sketches represent the topic. Skill at drawing was therefore unnecessary. Practice sessions were intended to be performed externally from classroom instruction and were expected to require 3 to 5 minutes. The drawings from each session were made on the sketching data collection sheets provided (see Appendix B), with each iteration drawn on a separate data sheet. Participants were asked if they used the video or previous sketches while drawing the current sketch iteration. At the time of the intervention assessment, the course instructor collected all sketch data sheets from the participants. If participants drew the sketch more than the required three times, they were asked to do so on additional data sheets. These sketches were collected as well. All collected materials were then transferred to the researcher, with the participant's study code serving as the only identifying information.

The outline group did not receive video access. Instead, they were provided with a topic outline that described the features of the process included in the model sketch. This group was asked to walk themselves through the outline, which was expected to require between 2 and 5 minutes. The outline group received their own data collection sheet (see Appendix C), on which the date and time required to review the outline was recorded for each session. The study required participants to log three sessions on three different days prior to the assessment. If the participant used the text outline to supplement further studying, these sessions were logged as well. At the time of the intervention assessment, the student participant returned their log sheet to the course instructor. The collected sheets were given to the researcher, with the participant's study code serving as the only identifying information.

Data Collection Variation: S3

For the introductory biology class at S3, all participants were shown the sketching video before being separated into two groups. The two participant groups were not assigned the same methods as S1 and S2. The first group at S3 used minute sketching with folded list (MSFL) methodology. This method of study is a step-wise process that allows students to review a particular topic in a short amount of time (Heideman, *MSFL Instructions*). To prepare their folded lists, students must first 1.) list keywords selected from the content, 2.) make a simple abstract sketch that encompasses these keywords, 3.) fold a piece of paper to divide it into at least four columns, 4.) write the keywords in the first column, and 5.) make their minute sketch in the second column. The sketch is intended to explain the keywords, so students are not allowed to write definitions. After verifying their understanding of the concept with class resources, students check that their drawing is as simple as possible while relaying the message of the keywords.

Once the minute sketch is developed, students could walk themselves through the sketch while identifying the keywords. Alternatively, the students could look only at the keywords and attempt to redraw the minute sketch. For both strategies, students are not allowed to guess but should refer to previous columns if needed. Through MSFL repetition (Figure 2), the students can fix both the keywords and the sketch into their memory. No S3 participant had used the MSFL method prior to the intervention. The introductory biology teacher, who was very familiar with MSFL, provided students with a workshop to teach the MSFL method. As a result, some specifics of MSFL were adapted for the purpose of this research to better suit the needs of

the students. Keywords and possible sketches were provided for each topic, and participants were not required to confine all keywords to representation by a single sketch.

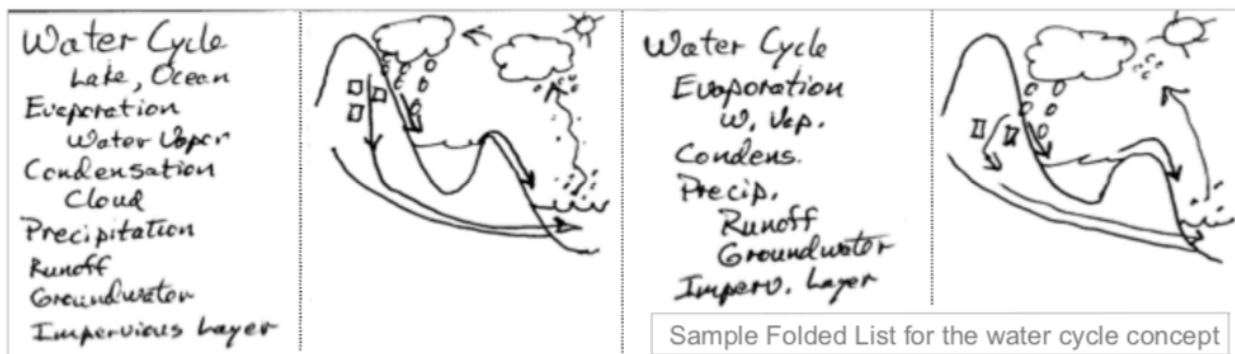


Figure 2. Example of the minute sketching with folded list (MSFL) technique for the water cycle. The example paper is divided into multiple columns, alternating between a list of keywords and an abstract sketch.

The second group in the S3 class did not use MSFL on the first topic, nor were they provided a text outline. Instead, these participants were separated from the MSFL group and instructed to use the time provided during class to review the content from the video using any method besides sketching. The method or methods used were recorded by students after each review session (Appendix D). Just like the other two sites, S3 participants were required to complete three review sessions on three different days prior to the intervention assessment. Materials were turned in to the instructor on the day of the assessment. Only after the first topic assessment was completed did the instructor show the students the video for the second topic.

Assessment Structure:

For each topic, participants were given a single-question assessment. Each assessment was a transfer question, which required recall and understanding. Participants were given the following written instructions on the assessment before reading the question:

*“Please work through the problem below in **any** way you choose. It doesn’t matter which group you were assigned to; you can answer using words, drawings, or a combination of both. If you choose to draw, however, you **must** also have your answer in words somewhere on the page. Please do not erase your work and answer on this side of the page only.”*

In answering the intervention assessment questions, students were required to respond with written text. The participant was allowed to develop their response in any way they chose. In other words, while the participants' final answers were in text format, the assessment instructions noted that a sketch can be made if the participant wanted to utilize it for concept recall or problem solving. The instructions might not have stressed these directives appropriately, as evident in some responses for which students' written text was used only to describe complex features of their sketches. To ensure objectivity and reduce potential bias in grading, the original intent was that only the written responses were scored.

Assessment Analysis:

Participant answers were graded using an adaptation of structure-behavior-function (SBF) coding (Hmelo-Silver and Pfeffer, 2004; Table 3). While scoring participants' written answers, a list of keywords present in both the video and the text outline was referenced. For the structure or descriptive aspect, each keyword present in both the student's answer and the list was awarded one point. Credit was given for behavioral or explanatory understanding if the participant described how these components work within the scope of the problem given. Credit for functional or integrative understanding was awarded for correct interpretations of the connections between the behaviors of key components. The number of points earned was significant for analysis only in the case of descriptive aspects. Explanatory and integrative understanding was coded simply based on presence or absence to reduce scoring subjectivity.

The terms in "SBF analysis" are misleading for biologists, because structure and function are often so tightly interconnected that neither is a comparatively "lower" or "higher" level of understanding. And the word "behavioral" as an adjective has a meaning in the biological sciences that is divergent from that in SBF analysis. In Table 3 below, we have used alternative

terminology that is clearer to us, and perhaps to other biologists. Throughout this thesis, we will use our terminology.

Level of Understanding		Example for Understanding of a Bike	Definitions
Structural (Lowest Level)	Descriptive	Bikes have two wheels, handlebars, a set of pedals, and a seat.	<p><i>“Elements of a system”</i></p> <ul style="list-style-type: none"> - Hmelo-Silver & Pfeffer, 2004 <p><i>“Surface features”</i></p> <ul style="list-style-type: none"> - Smith et al., 2013
Behavioral	Explanatory	Pushing down on the pedals makes the wheels turn. The seat allows a person to ride the bike comfortably	<p><i>“Mechanisms” of a system</i></p> <ul style="list-style-type: none"> - Hmelo-Silver & Pfeffer, 2004 <p>[How elements operate individually within the context of the system]</p>
Functional (Highest Level)	Integrative	The bike will only turn if the handlebars are rotated as the wheels are moving. The person in the seat riding the bike must use energy to pedal with their legs while also turning the handlebars to make a turn.	<p><i>“A network of concepts and principles... [representing] key phenomena and the interrelationships among different levels of the system”</i></p> <ul style="list-style-type: none"> - Hmelo-Silver and Pfeffer, 2004 <p>Acquired through <i>“generative processing”</i></p> <ul style="list-style-type: none"> - Mayer, 2009

Table 3. Levels of understanding coded in participants’ responses. The structure-behavior-function (SBF) coding scheme was adapted from a manuscript authored by Hmelo-Silver and Pfeffer (2004). The column in the middle provides a very simplistic example.

End of Study Period:

At the end of the study period, another online survey was distributed to participating classes. This survey included the pre-survey questions pertaining to study methods and an additional question that asked student participants to estimate the usefulness of sketching methods. All paper files were held in a research laboratory on the William & Mary campus, and electronic files were saved on a secure server. Survey answers, sketching and outline data sheets, and intervention assessments are connected to the participant only through their study code.

Note: Data and post-surveys from S3 participants will not be available for this thesis, because the collection phase is still in progress. Part of this is due to our efforts to produce pilot materials that were designed to be workable within teachers' current schedules. Instead of restricting site participation by requiring procedural discipline, we have chosen to be flexible so that participation was accessible. As a result, different teachers have requested modifications to be made to the protocol to match their instructional goals or instructional style. Because this research is intended as a pilot study, we accommodated these requests.

Results

In this section, our presentation is separated into three categories: study methods, assessments, and site variability. For each category, we discuss our findings and relevant interpretations. Later in the thesis, we provide an integrative interpretation. Some of the data and results that we did not use for the discussion were removed to an appendix (Appendix E).

1. Study Methods: Findings

Students in each of the three classrooms responded to an online survey disseminated by the class instructor prior to intervention data collection ($n = 59$). Four pre-surveys left incomplete (defined as $<50\%$ done and lacking a study code) were omitted from analysis. Out of 55 student responses, 19 were from freshmen (34.5%), 33 were sophomores (60%), and 3 were from upperclassmen (5.5%). Student respondents from S1 represented grades 9-12, while all S2 responses were made by freshmen ($n=16$), and all S3 responses were from sophomores ($n=16$). Regardless of grade level, the majority of students in each class cited their reason for taking the

class as a graduation requirement. Seven respondents (13%) also identified their biology course as involving a career interest, and nearly a third included a personal interest in the course (31%).

The pre-survey focused on the study methods used by respondents. Before the survey was disseminated, a list of 17 study methods were labeled as “active” or “passive” based on operational definitions from the literature (Heideman et al., 2017; Table 4). These study methods were presented to students without their labels, and students were asked to select all of the methods they used for science courses (Figure 3). The average number of passive versus active methods used by students prior to the intervention was roughly equivalent; 2.2 and 2.3 respectively. However, of the study methods self-reported by students, the largest average percentage of time (39.5%) was devoted to the passive method involving rereading their notes.

Passive Methods (6)	Active Methods (11)
Reading over notes	Making concept maps*
Rewriting notes	Making diagrams*
Reading class PowerPoints or other lecture materials made by the instructor	Studying diagrams*
Rereading the textbook	Making drawings and sketches
Summarizing class materials to make a study guide	Redrawing sketches
Highlighting	Using mnemonics
	Doing practice problems
	Self-testing
	Taking practice tests
	Making and using flashcards
	Retrieval practice

Table 4. Study method categorization; passive versus active (from Heideman et al., 2017). Methods marked with “” are those not directly stated in Heideman et al., 2017.*

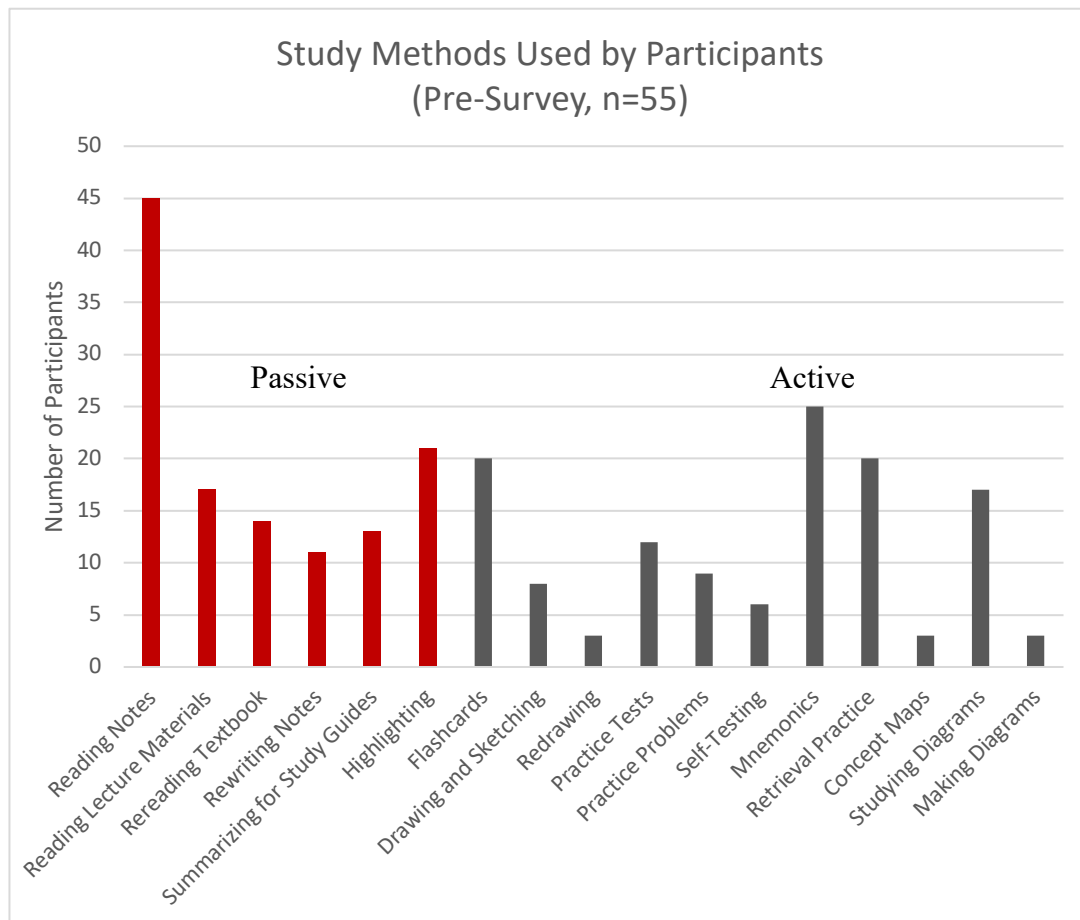


Figure 3. Participants' study methods prior to the research were self-reported on an online survey. All passive methods are on the left represented by red bars, while active methods are represented in gray on the right side. The average number of study methods used by participants was 4.5, with a range from 0 (participant did not study) to 13 of the 17 listed methods.

When freshmen were compared with sophomores, there was no significant difference between the number of study methods used or the percentage of time spent using active or passive methods, nor were there significant differences for the average amount of time spent on individual methods. Significant differences were identified between freshmen and sophomores in the average time spent for only two passive study methods, rereading the textbook (Welch's two-sample t-test, $p = 0.0158$) and highlighting ($p = 0.0221$), but these were not significant when the tests of 17 different study methods were evaluated using the false discovery rate control

(Glickman et al., 2014). Therefore, freshmen and sophomores were combined to form a single underclassmen group for study.

Only eight students reported using sketches or drawings in some form prior to the intervention (average 13% of study time). Of these 8, only 3 reported iterative practice redrawing their sketches. Twelve students reported summarizing course materials to make study guides prior to the research (average 11% of study time); this was considered during analysis to be the closest available match to the text outlines we provided in the intervention. Only two students reported having sketched and made study guides; both reported spending more time sketching than making study guides.

After the research assessments were complete, S1 participants were asked to complete a post-survey on the Qualtrics platform. Surprisingly, some participants reported different time allocations for study methods, and others reported fewer study methods used altogether. For example, one of the participants had indicated using drawing as a study method prior to data collection; after iterative review of two topics, their self-reported study time spent drawing was reduced by 20%. Another participant indicated on the post-survey that they began to allocate study time (10%) to drawing. While this student could have recounted the time spent sketching for the research study, it is possible that sketching methodology was adopted. Certain participants reported increases in other active methods; one reported doubling their amount of retrieval practice, another reported beginning to use practice problems (33% of study time), and a third participant began using practice tests (50% of study time).

2. Study Methods: Interpretation

No significant change in student study methods was expected for the post-survey. No feedback was given to students after the assessment to provide them with information regarding

a study method’s effectiveness in relation to achievement to influence future study methods. The time interval over which the study was conducted was relatively short, making it unlikely students would alter their study habits significantly. Yet when analyzing post-survey data for S1, differences in the number of reported study methods were present (Figure 4), raising questions regarding the validity of post-survey responses. We propose that respondents may have recognized the question from the pre-survey, anticipated the carry forward question that followed, and were unwilling to expend additional effort in estimating percentages of time spent with each method, and therefore reported fewer study methods. To address this potential survey fatigue in future studies, the time estimation question could be removed from the pre-survey and reserved exclusively for the post-survey. If we require time estimates for both time points, however, we could ask respondents to select up to three methods they use the most from the list and provide time estimations for these methods exclusively.

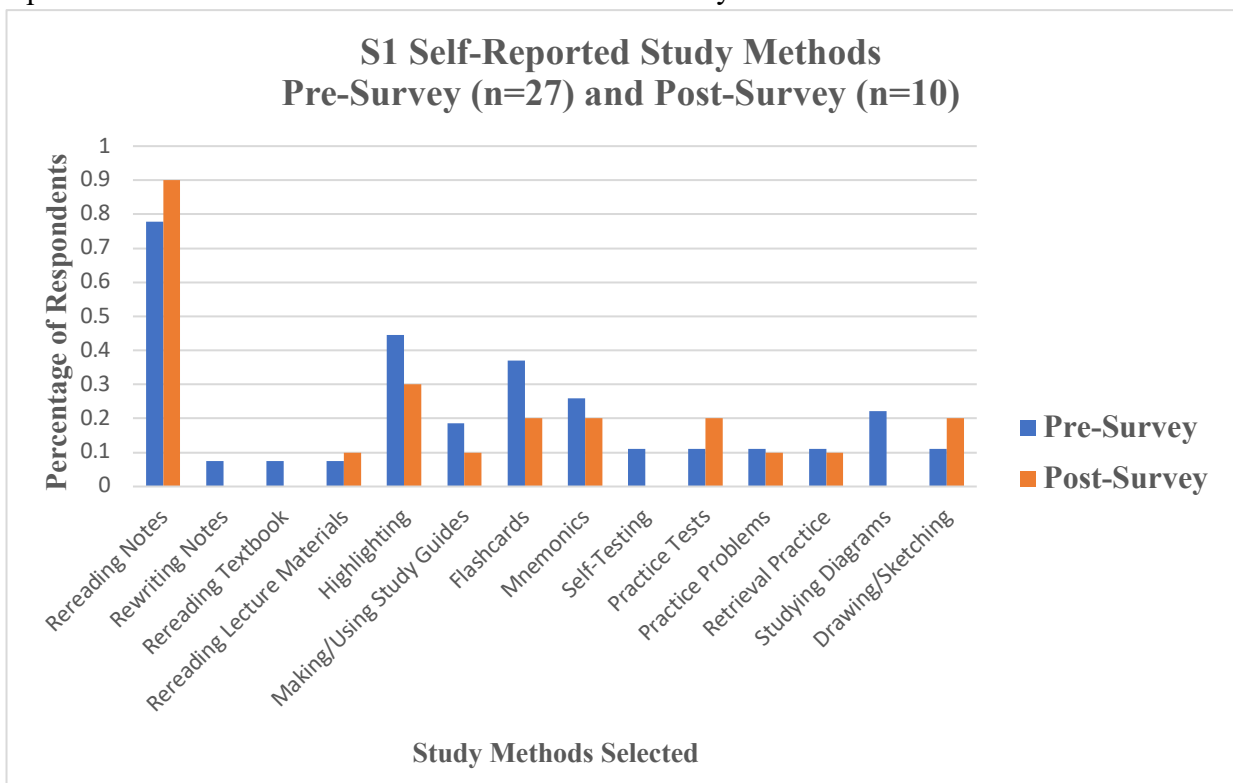


Figure 4. Comparison of S1 students’ reported study methods used before and after data collection.

3. Assessments

After participants completed three review iterations on three separate days for one or both topics, the course instructor distributed an assessment. The assessment questions that were used at S1 and S2 are provided in the table below. In coding the assessments, the analysis was carried out in the same manner for each topic question.

Site	Topic	Assessment Question
S1	Protein Channels	<i>How do protein channels allow only specific molecules to pass through?</i>
S1	Enzyme Function	<i>What characteristics would an enzyme need in order to split a triangle-shaped substrate molecule with positive and negative charges?</i>
S2	Cell Scaling and Allometry	<i>Suppose an elephant's body dimensions increased by a factor of 3. Should an elephant compensate for this increase by shortening its legs? Provide an argument that explains why or why not.</i>
S2	Cell Cycle Checkpoints	<i>A drug is added to a cell culture that blocks proteins that cause cell death. How would this affect a cell with no DNA damage? What about a cell with significant DNA damage?</i>

Table 5. Assessment questions used at S1 and S2, with no topic overlap between the two sites. The protein channel question at S1 was modified to be a recall-based question as opposed to a transfer-based question; this allowed students to formulate a response that could be collected. The first assessment question from S3 can be found in Appendix D.

4. S1 Assessment Findings

Two assessments for the protein channel topic could not be included in analysis because it was impossible to match them to a specific participant; indicating that these students possibly did not turn in the consent form with parent authorization.

For S1 questions, there were 8 keywords for each topic question; each granted one point to a participant score for descriptive understanding. Each keyword was a surface feature mentioned in the video as well as the text outline (see Appendix F). The S1 scores for descriptive understanding were very poor (Figure 5). For the protein channel question, the average descriptive score for the outline group was 1.4, while the average score for the sketching group was slightly higher at 1.8. The difference in descriptive point averages was similar for the transfer question involving enzyme function; the outline group identified an average of 1.3 keywords, while the sketch group again identified an average of 1.8 keywords. The number of keywords identified by participants is very low, between 16 and 23% of the total possible. Several qualifiers must be acknowledged before discounting students' descriptive understanding entirely. When analyzing written answers, we were very strict with awarding points in order to be as objective as possible. The only words or phrases that received credit were those included in the students' answers verbatim. This avoided artificial inflation of the data and mitigated experimenter assumptions of student understanding. Yet with the small sample size ($n=10$; $n=8$) and a potential for confounding variables, the difference between group averages is insufficient to suggest that sketching meaningfully affects descriptive understanding of S1 students.

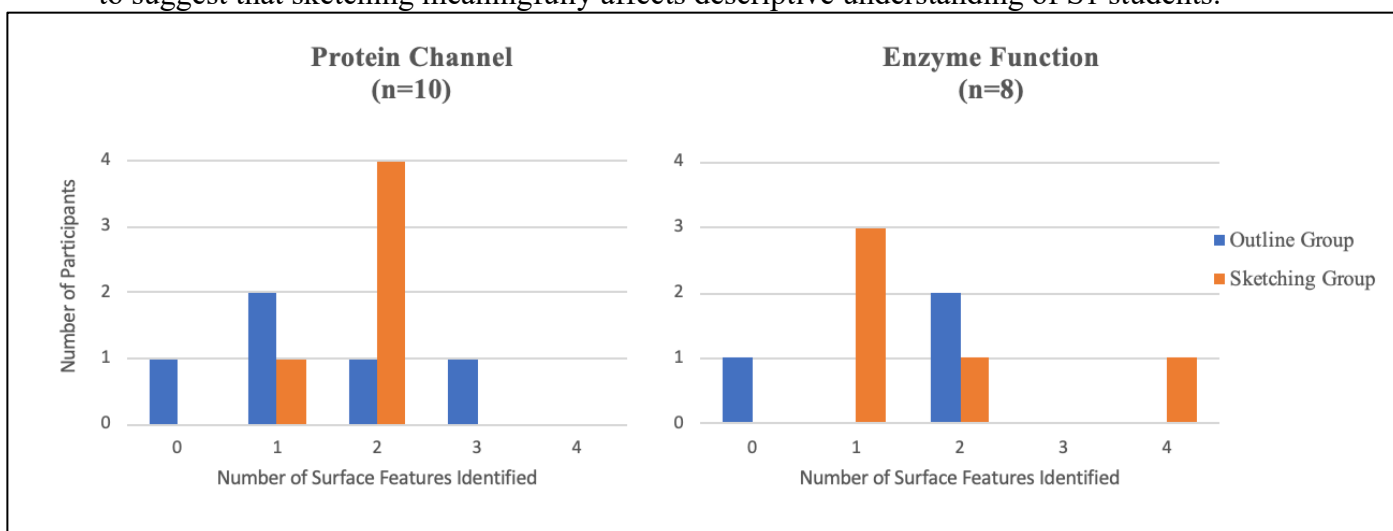


Figure 5. Surface features identified by S1 participants for each assessment question.

For the question about protein channels (PCQ), 3 students exhibited explanatory understanding. Explanatory understanding for PCQ was demonstrated by text describing charge-matched molecules passing through the channel opening or “*the cell membrane to enter the cell*”. Integrative understanding was recorded when a student described opposite charge matching between the channel and the molecule it allows through. Based on PCQ written responses alone, only one participant approached integrative understanding. Their answer, “*Protein channels allow molecules to pass through because of the distribution of charges. They have openings for molecules to pass through,*” does not indicate charge matching. But without a think-aloud interview, it would be impossible to exclude integrative understanding. In an interview, the student would be asked to clarify how the distribution of charge affects protein channel selectivity.

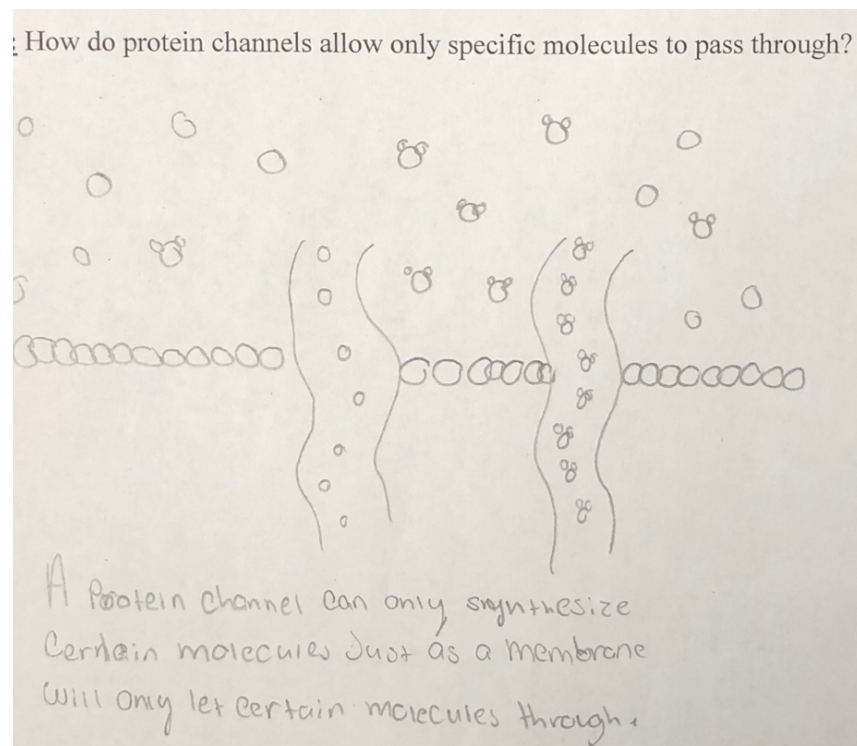


Figure 6. Student response to PCQ. While the written response does not indicate explanatory understanding, the sketch accompanying the text demonstrates near complete explanatory understanding.

The above analysis includes only participants' written answers, but analyzing student drawings in addition to text responses may more accurately reflect understanding. While looking through the assessments, it became apparent that additional responses would have approached explanatory understanding had drawings been analyzed as well as written responses. In the example in Figure 6, the sketch did not fully describe protein channels, but it exhibited molecule selectivity. The written response did mention that "*certain molecules*" are allowed through but includes errors such as attributing channel selectivity to the membrane as opposed to the protein channels. The membrane in the sketch is distinctive from the squiggly lines that are representative of protein channels, and the student shows selected molecules moving through these channels. In another example, if sketches were included in the assessment of integrative understanding, a participant would have received credit for this level as well. Though the participant described molecule selectivity based upon "*polar codes*", their sketch demonstrates they understand that selectivity is based on opposite charge interactions (Figure 7).

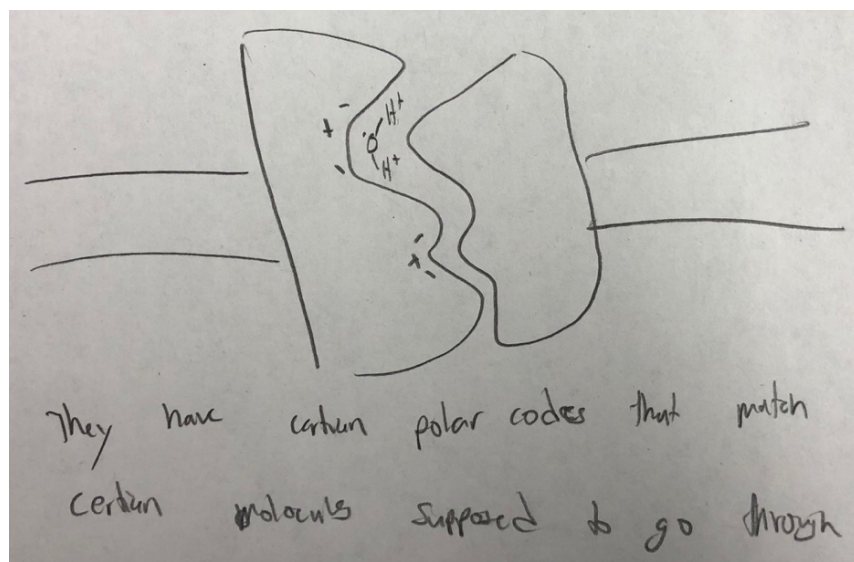


Figure 7. While this participant describes "*polar codes*", they demonstrate explanatory understanding of protein charges by indicating selectivity as a result of charge in the accompanying sketch.

The question about enzyme function was a transfer problem that we assessed as requiring more problem-solving skills than the question about protein channels, but 3 students were nevertheless able to demonstrate explanatory understanding in their responses. Their answers described opposite charges holding the substrate, the specific shape of the enzyme in order for the substrate to fit, or random molecular movement causing the enzyme to change its shape. Two of the three students were in the sketching group and included a sketch in their answer. One demonstrated integrative understanding only in their sketch, unlike the other who demonstrated integrative understanding of enzymes in both text and sketches (Figure 8).

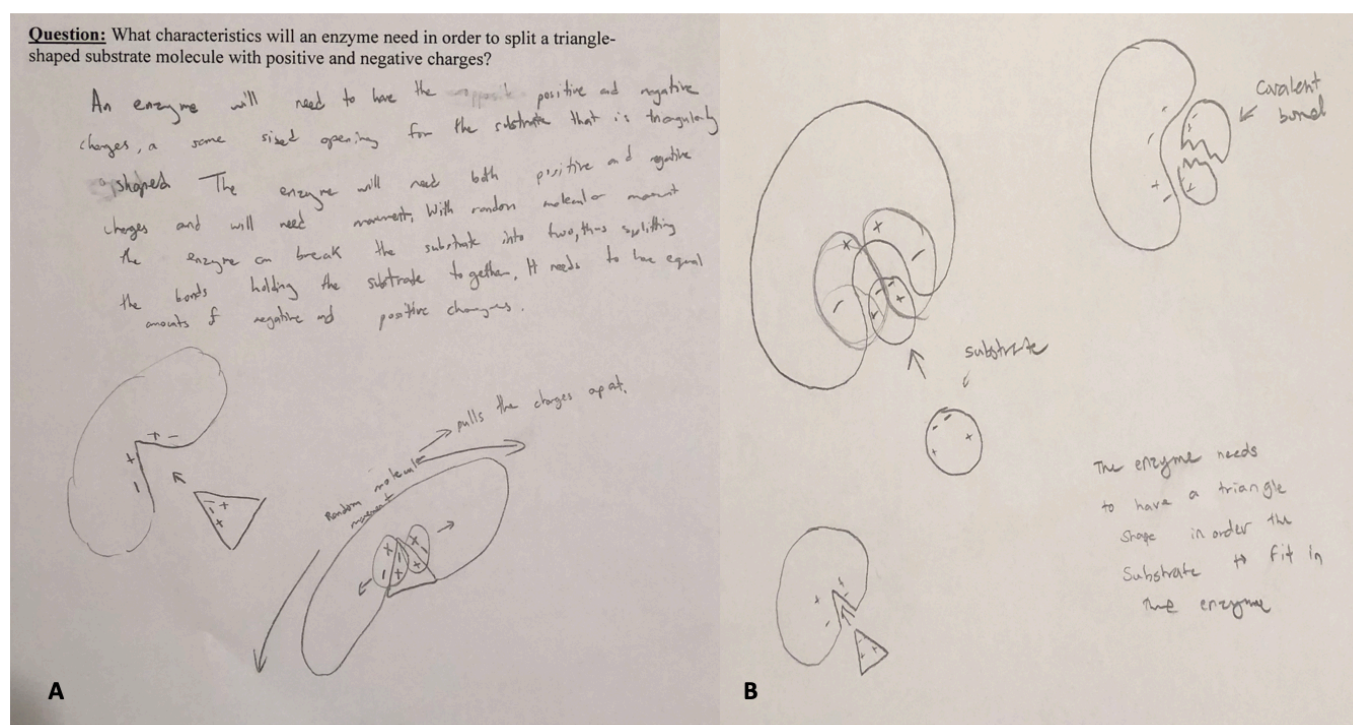


Figure 8. Two participant responses to the transfer question about the enzyme topic; a.) received credit for full integrative understanding with text alone. For b.) the sketch is necessary to demonstrate this student's integrative understanding.

5. S1 Assessments: Interpretations

Two S1 participants were able to demonstrate explanatory understanding for both questions, but only demonstrated integrative understanding in their responses to the question they received after being in the sketching group. Though the data are insufficient to infer

causation, the connection between sketching and integrative understanding might prove significant in later studies with larger sample sizes.

An underlying issue became apparent from S1 assessments: there were gaps in student understanding that were not addressed by the study materials provided. A majority of answers suggested gaps in background and prior knowledge. One participant in the sketch group drew each iteration with the channel as an open gap at a swelling in the bilipid membrane (Figure 9). This aggregate of protein and lipids would have very different ramifications on transport than the protein channel structure modeled in the video. Several other participants anthropomorphized channel proteins for channel specificity; one participant wrote that the channel “*fights off*” the *bad ones*”, only letting things pass if they were “*good*”, while others stated that the channel “*knew*” which molecules to let pass through to the interior of the cell.

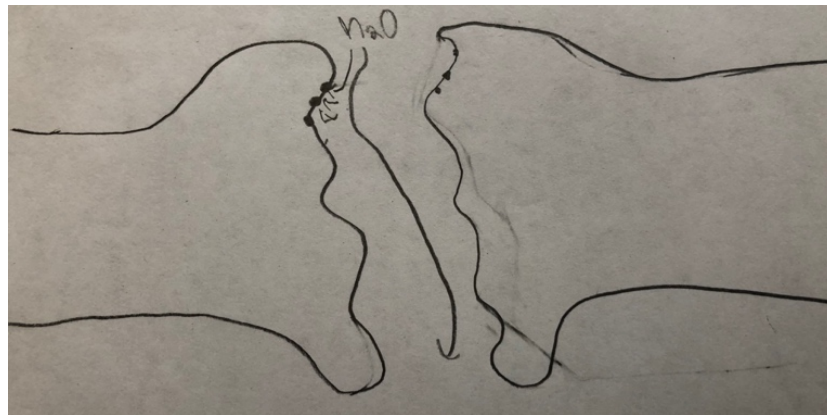


Figure 9. Participant drawing of a protein channel; here, the channel is indistinct from the bilipid membrane represented in the sketch.

Other misconceptions stemmed from a misunderstanding of biological size relationships. For example, one participant stated that protein channels allow specific cells to pass through them. Given that the average human cell is about 20 microns in diameter and an average membrane protein is 3 orders of magnitude smaller at approximately 6 to 8 nanometers wide, it would be impossible for a cell to pass through a protein channel.

Occasionally, participants indicated a lack of prior knowledge in their descriptions of function; one student responded to the assessment that protein channels “*synthesize*” certain molecules that pass through the channel (Figure 6). Another participant indicated that “*protein channels use enzymes to break down specific molecules so they can fit through*”; while this student indicated specificity later in their answer, they attributed this specificity to enzymes as opposed to the channel’s distribution of charge. Though some products of enzymatic breakdown (catabolites) can travel through protein channels, catabolism is not a prerequisite for movement through a protein channel, nor do channels partner with enzymes. The narrated sketch video indicated no need for enzymes with its two examples, transport of water and charged ions across the membrane.

One clue to missing background knowledge was the vague language used by some participants. For example, to split a charged substrate, one response said the enzyme must “*move through to get to a triangle-shaped substrate*”, showing no descriptive, explanatory or integrative understanding. Another answer described “*shells*” that allowed the enzyme to hold positive or negative charge “*so that they’re split up*”. After being asked to describe the characteristics of the enzyme, some students answered with descriptions of the substrate instead. A participant indicated that the substrate “*needs negative on both ends*”; another responded that “*all molecules have to have the same positive & negative affect to one another*”.

At S1, the question about protein channels was objectively easier than the question about enzyme function because it did not involve transfer (Mayer, 2009). Yet after participants had taken both assessments, their combined ratings difficulty for each question was the same. This indicates that the lack of sufficient background knowledge similarly affected their ability to

answer either assessment question. Alterations to account for limitations in background knowledge are included in the discussion of this paper.

Even though the data are not strong enough to suggest sketching develops a student's level of understanding to a greater extent than other passive study methods, student sketches are still valuable in the high school classroom. Although participant misconceptions lowered assessment response scores, detecting these misconceptions may prove valuable to educators (Ainsworth et al., 2011; Quillin & Thomas, 2015). Teachers could detect student misconceptions that had gone unnoticed when introducing content to students. Then they could address the misconceptions to enhance student understanding. In the case of the protein channels, some misconceptions were identified from student sketches, while others were evident in text answers to the intervention assessment. For the enzyme transfer question, misconceptions were noticed by reading student responses. To better understand where these misconceptions developed, it was often more helpful to turn to student drawings for those in the sketching group. When students sourced their information from an outline, uncovering details of how the student came to the misunderstanding was more difficult. With passive methods, a student's thought processes were invisible. If an assessment response was incorrect, it was often too difficult to point to the exact misconception. Errors in drawings, by contrast, can point to the exact information within a topic that isn't being fully understood.

6. S2 Assessment Findings

Nine participants completed both rounds of iterative review followed by a combined assessment. The assessment questions for S2 were about cell scaling and cell cycle checkpoints. Participant responses were coded for descriptive understanding by comparing written responses to a list of keywords (Figure 10).

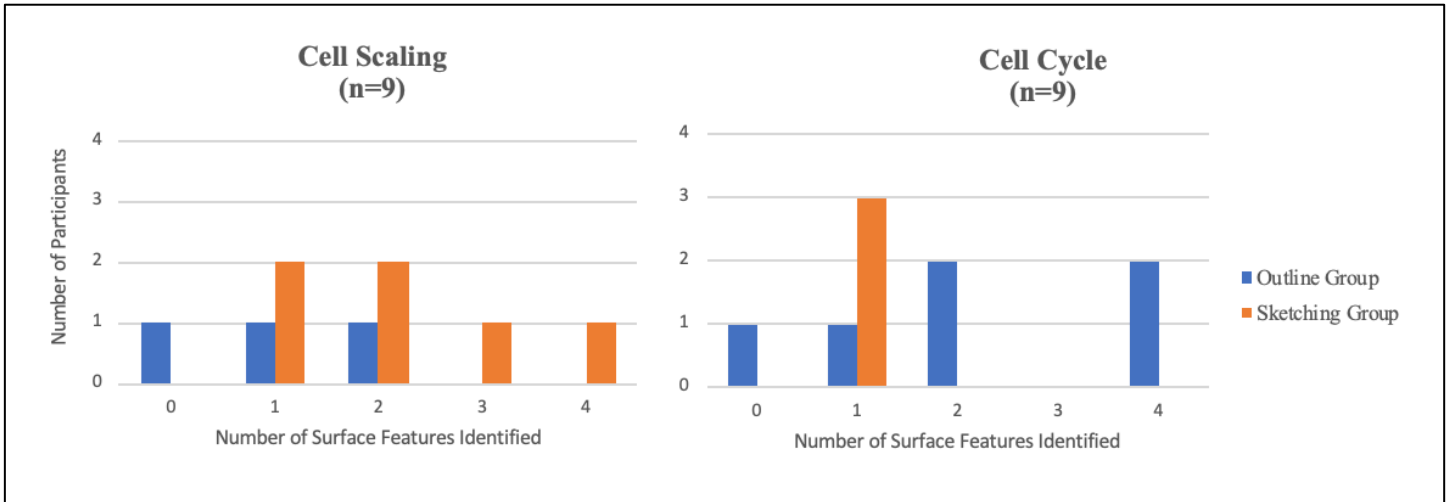


Figure 10. Number of identified surface features (structure scores) for each S2 topic question. Participants that used sketches in one topic were the same students using outlines in the other topic.

There were 8 possible keywords for the cell scaling topic and 7 for the checkpoint topic. The average number of surface features identified was 1.8 for both questions, corresponding to 22% for the cell scaling and 25% for the checkpoint transfer question. For each question, 1 participant identified over half of the surface features (Figure 11), but the low average values might be due to the same conditions affecting S1 descriptive scores.

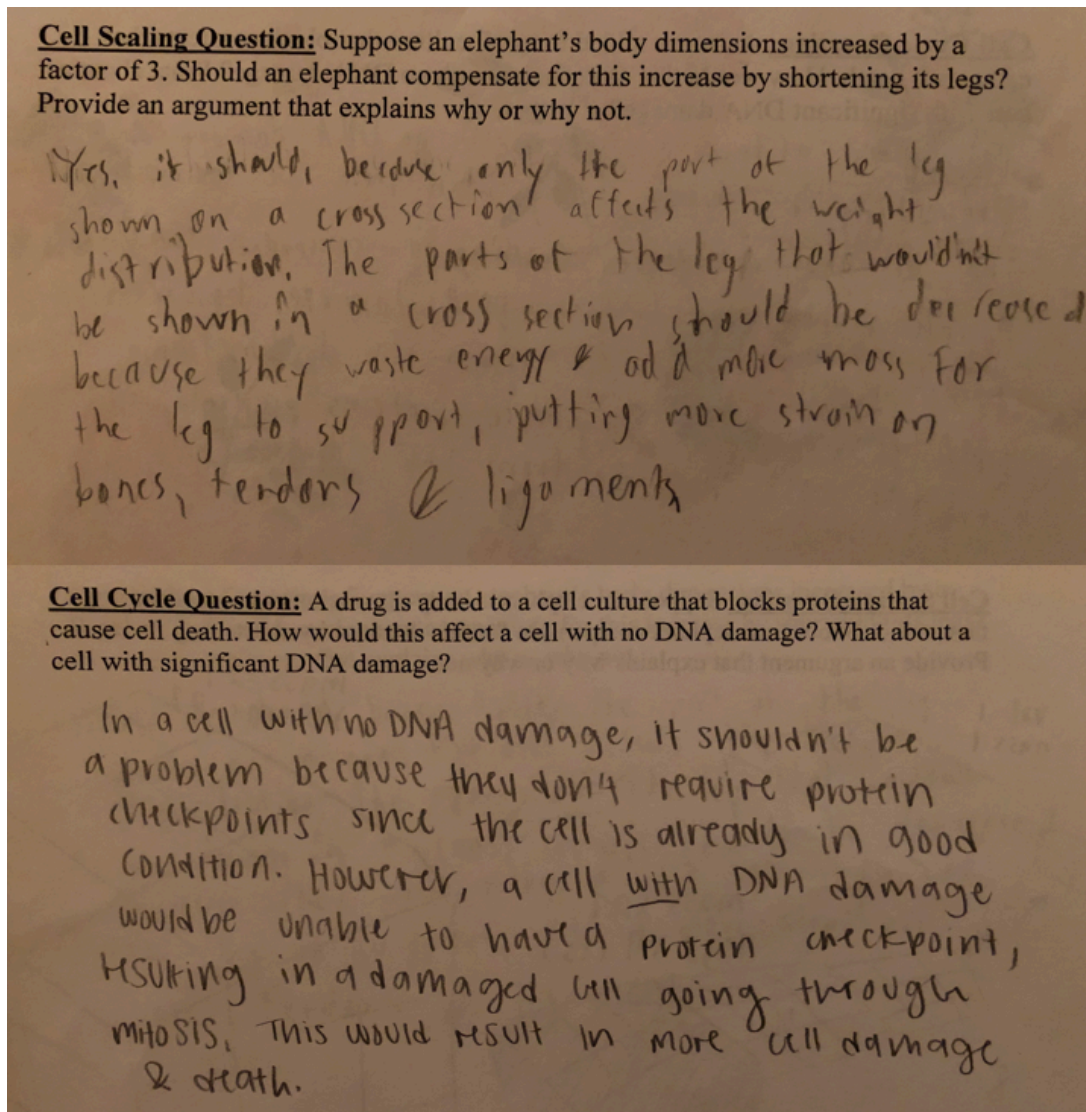


Figure 11. Participant answers with more than half of the selected keywords for surface features. The response at the top answers the question about cell scaling, and the response on the bottom answers the question about cell cycle checkpoints.

For the scaling question, the average number of identified surface features was twice as large in the sketching group (2.2) when compared to the outline group (1). The same was observed in responses to the checkpoint question, but the outline group identified twice as many surface features than the sketching group. Because the averages of surface features identified is the same for each group of students regardless of experimental condition, this indicates that sketching may not have impacted descriptive understanding in this group.

In written responses to each of the transfer questions, 5 out of 9 (56%) S2 participants demonstrated explanatory understanding. For the cell cycle question, participants indicated that significant DNA damage causes cell death under normal conditions or stated that the drug will not affect the cells with no DNA damage; either of these indicated an explanatory level of understanding. The proportion of participants demonstrating explanatory understanding did not increase when SBF coding included drawings present in the participant responses. For the scaling question, students said that the increased volume results in increased mass, that must then be distributed among the elephant's four legs. When the drawings were coded in addition to students' written responses, two additional participants from the sketching group received credit for explanatory understanding (Figure 12).

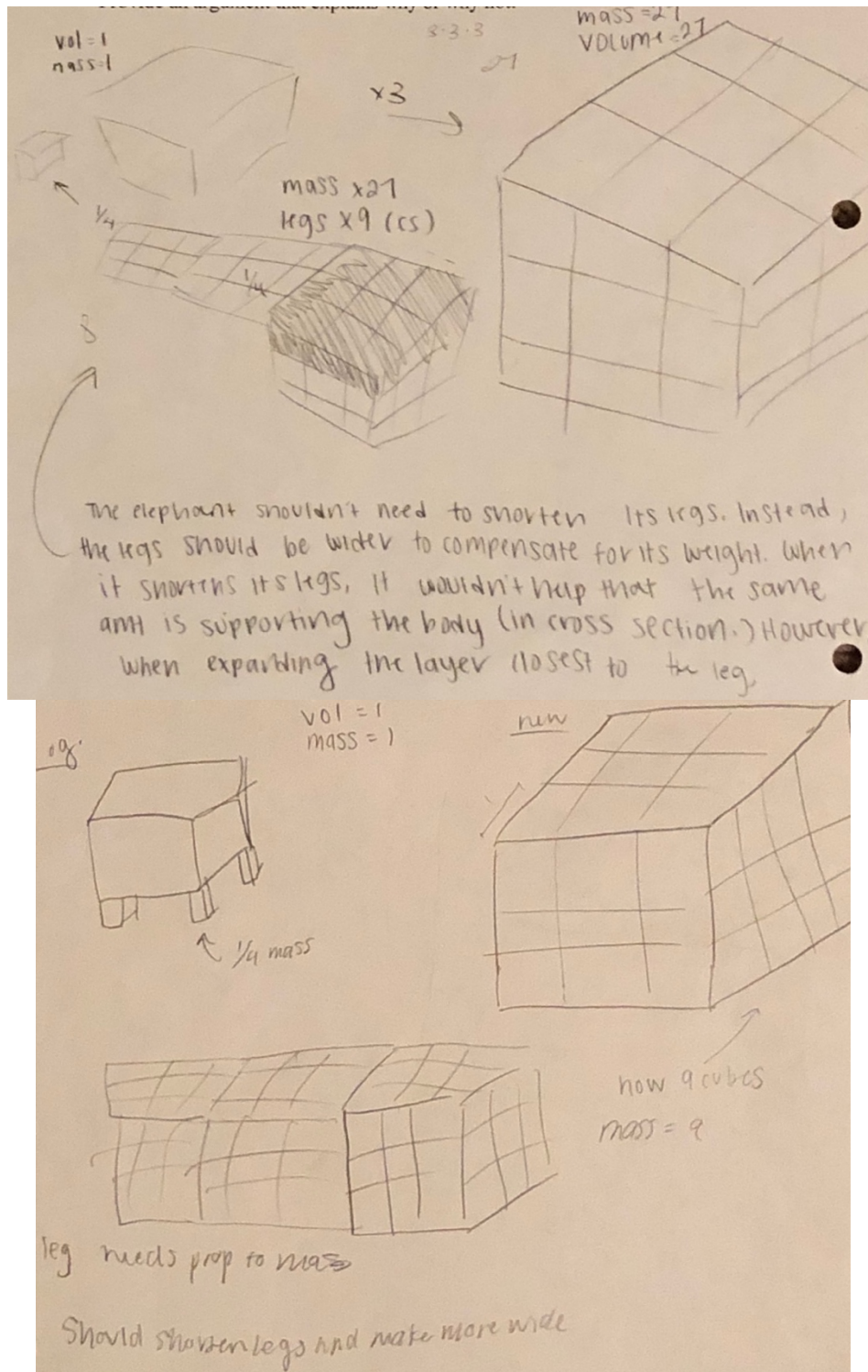


Figure 12. Participant responses to the transfer question about scaling. If the sketch included in these participants' answers were coded, the student would have demonstrated explanatory understanding.

For the transfer question about cell scaling, 2 of the 9 participants (22%) were credited for integrative understanding. In addition, the 2 participants who demonstrated explanatory understanding through their drawing would have also received credit for integrative understanding for a total of 4 out of 9 (44%). For these participants, explanatory understanding was exhibited through a sketch, but integrative understanding was present in their written response (Figure 12). Their answers appeared to use drawings as their primary response, adding writing to provide additional information about their drawings, even though instructions stated that grading would be exclusively based on written text (Figure 12).

Five of the 9 participants (56%) demonstrated explanatory understanding for the question about the checkpoints of the cell cycle, and 4 participants (44%) demonstrated integrative understanding. Integrative responses explained that the drug allowed damaged cells to continue to multiply or described the DNA damage checkpoint as no longer operational. Neither of these proportions increased when drawings were coded in addition to written answers.

One participant who received credit for explanatory understanding without integrative understanding for the transfer question about the cell cycle only described the checkpoints for DNA damage under normal conditions. The following table compares this answer to another written response with evident descriptive, explanatory, and integrative understanding.

Explanatory Understanding	Explanatory + Integrative Understanding
<p data-bbox="178 237 797 415"><i>“If DNA [is] damaged, then [the cell] cannot continue to the next phase [of the cell cycle], therefore no division. If DNA unaffected, then [the cell] may continue to [the] next phase and could possibly divide.”</i></p> <p data-bbox="178 436 797 611">[This answer describes the system under normal conditions rather than in the context of the transfer problem, therefore lacking integrative understanding; in the scenario provided, even the damaged cell would divide.]</p>	<p data-bbox="821 237 1421 489"><i>“In a cell with no DNA damage, it [the drug] shouldn’t be a problem because they don’t require protein checkpoints since the cell is already in good condition. However, a cell with DNA damage would be unable to have a protein checkpoint, resulting in a damaged cell going through mitosis...”</i></p>

Table 6. Comparison of text responses to the transfer question about the cell cycle checkpoints. The response on the left indicates explanatory understanding, but does not exhibit integrative understanding. The response on the right, by contrast, exhibits integrative understanding because it indicates that the damaged cell would divide and replicate.

7. Site Variability

Through collaboration with the site instructors, the protocols were modified at each of the three sites. The transfer question about protein channels (S1) was simplified, without which students were unable to provide a response. At S2, as a result of interruptions to the school schedule, the intervention assessment was consolidated into a single test composed of two questions. Consolidation may have saved class time, but required participants to review both topics at the same time, thus departing from protocol requirements. S3 used a variation of abstract sketching methodology called minute sketching with folded lists (MSFL; Heideman et al., 2015). The non-MSFL group was not restricted to text outlines for iterative review sessions, but was instead allowed to study the topic using any method except sketching. Both groups’ review sessions were completed during class time, after the classroom instructor provided a workshop on MSFL.

Instructors from S1 and S3 mentioned that their students became visibly interested in the new study techniques and accompanying materials. Part of this interest likely stemmed from the instructors’ enthusiasm for the techniques, which had been communicated to us at the time of the

request to participate. The S1 instructor had been facilitating visual representations as fluent recall tools, especially for class projects. The S2 instructor was familiar with visual learning methods but had not had the chance to implement such methods in the classroom and was therefore willing to test them through this study. The S3 instructor was already knowledgeable about MSFL and was enthusiastic about teaching the method to his students. Instructor interest was critical; student investment in the research was nearly impossible for us to facilitate as outsiders. Because the participating teachers were the driving force behind student engagement in the research, variations were important to accommodate.

Discussion

The goal of this honors thesis was to test whether 1.) high school students could apply sketching techniques to standardized content, 2.) they were able to use a sketch as a basis of SL understanding, and if so, 3.) could we measure the effects of sketching as an MBR tool. Transfer assessments were used to measure how the students were using sketches after receiving narrated multimedia videos of sketches. This research developed materials and provided informative pilot data. Alterations could be made to increase the fidelity of implementation.

The final small set of 3 science teachers from an initial group of 7 led to a small sample size; it was difficult to work through the steps to implementation with teachers unfamiliar with the researchers. When teachers chose to participate, administrative approval was also required. In each of the three cases, the approval process began after the Human Subjects Committee at the College of William & Mary approved the project. At S2 and S3, this entailed a letter of acceptance written after review by the school director. For research to begin at S1, the project

needed to be approved by the county School Board's central office. Administrative processes all took months.

The participating teachers made a significant difference in project outcomes. As a result, it is tempting to suggest that they be provided a greater role in the project. But with increased responsibility and possible authorship, at least two challenges arise. The first is that it would be more difficult for teachers to use their own classes for data collection, as it is unconventional for researchers studying K-12 schools to use their own classes as sample populations, due to the risk of experimenter bias. Second, extensive time and effort would be required to train these teacher-authors to then train their colleagues to collect data, necessitating a wider network of participating teachers and schools. To enhance the fidelity of implementation – correctly applied procedures in the desired sequence without bias – training should be under control of the researchers.

After editing materials to each instructor's recommendations, we expected students to have the adequate background knowledge to answer the instructor-approved transfer questions provided. However, we learned that even with instructor approval, some questions were too difficult at some sites; high-school level understanding varied between high school classrooms and among the participants themselves. We initially thought we addressed this by coding higher levels of understanding by presence or absence of keywords. But perhaps the quantitative measurement of integrative understanding is not feasible.

Using written answers alone to assess understanding was not optimal in assessing participants' understanding. In some cases, participants demonstrated higher levels of understanding through a drawing than through their written text (Figures 7, 8 & 12). In one example, written text explained only a nonobvious feature of the sketch (Figure 8b), while

evidence for deeper levels of understanding was found in the drawings. This creates a problem we have not solved. When coding sketches in addition to written responses, those with sketches may be scored more highly because more information is assessed; students assigned to the sketching group might receive inflated scores (Figure 13). But disallowing participant drawings in assessment responses would limit students' answers if the drawing is part of a mental model and used for MBR.

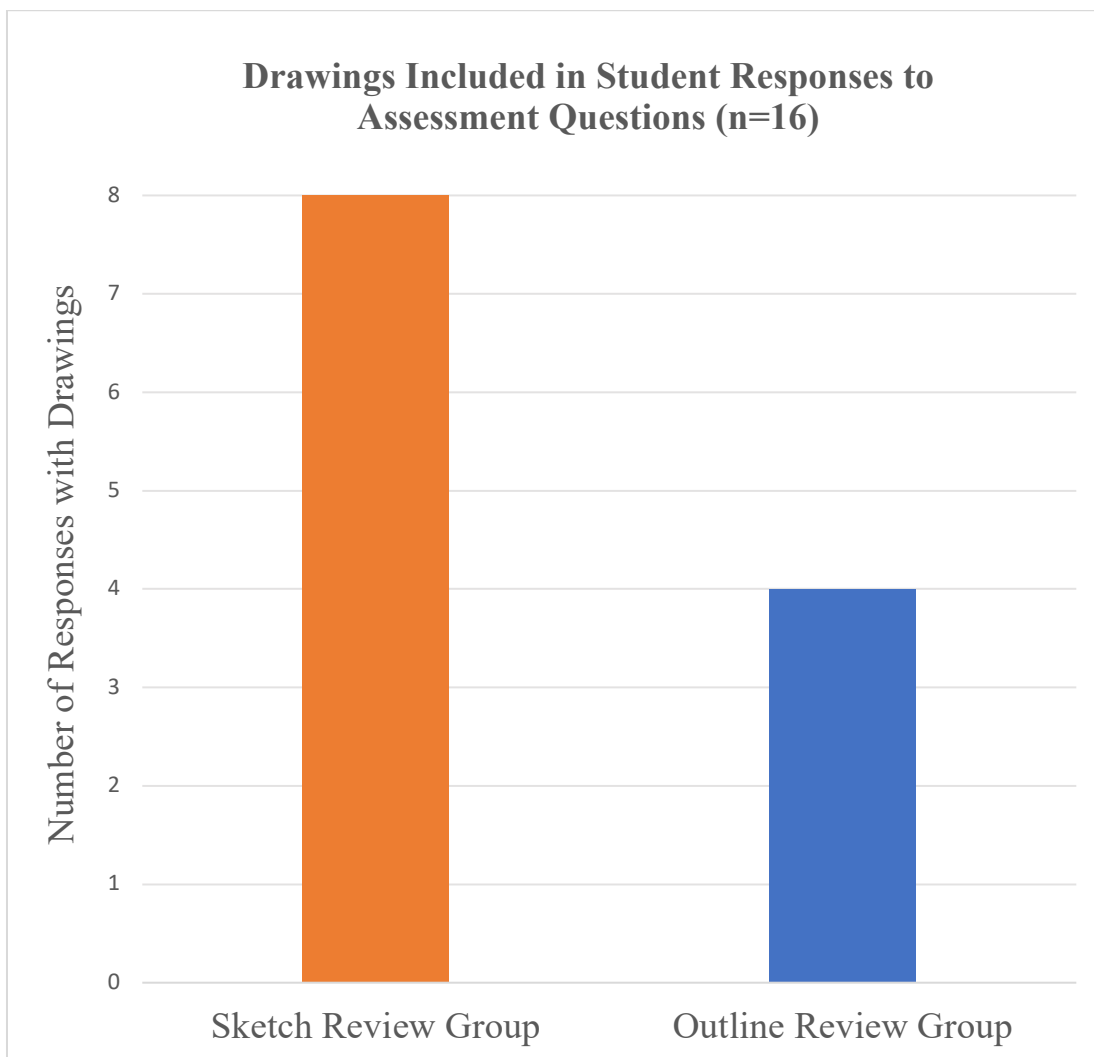


Figure 13. Participants in the sketching group were more likely to include a drawing in their response to intervention questions. The data above were taken from 16 students' answers responding to two transfer questions. The difference between the number of drawings across the two groups is statistically significant ($p < 0.05$).

To begin to address this dichotomy, we can adjust research materials so both groups are likely to include drawings in their responses. Instead of providing one group with text alone, for example, we can incorporate textbook figures in the outline. These selected figures could be representational rather than abstract to differentiate the figures from the narrated sketches in videos. In the assessment instructions, we would encourage students to respond to the transfer questions with whichever methods they choose. If this proposed adjustment receives similar criticism, we would still need to find other measurable features that distinguished students with integrative understanding or MBR skills.

1. Potential Boundary Conditions for Quantitative Inclusion

Our protocol could be altered to allow teachers to use their own classrooms as sample populations while mitigating the described limitations by using boundary conditions to enhance fidelity of implementation. Boundary possibilities include selection for prior knowledge of students, intervention start time, and materials adjustment. Flexibility within boundaries may require teachers already familiar with abstract drawing methods for models and MBR.

a. Selection for Background Knowledge

As discussed earlier, we observed a mismatch between student ability and the materials we provided. Especially at S1, a lack of background knowledge reduced the strength of preliminary inferences. The mismatch may be in our materials; students could have missed keywords that were too specific or were not adequately emphasized in the iterative review materials. Alternatively, the mismatch may have been surface feature keywords that relied on a knowledge structure that some students had not already developed. A student who has not acquired the fundamental idea of proteins as distinct from lipids cannot distinguish these as separate surface features (Figure 9). With a small sample size and researchers' separation from

the classroom, it is not yet possible to distinguish between study materials that are missing information versus a student's incomplete background knowledge.

Minimizing the unreliability described above can be addressed through the addition of a selection component for participants' capability to transfer prior knowledge or the expansion of the materials library. The first suggestion, adding a "selection step" for background knowledge, might be more difficult. Producing a qualifying test for generalized background knowledge may inadvertently filter out students who have highly developed explanatory and integrative understanding for specific topics. The second suggestion might involve participants watching more than one narrated video before iterative review. Rather than being isolated as the only review item, the selected video could be the final in a sequence intended to address background knowledge needed to adequately answer the transfer question on the intervention assessment. To standardize background content, this information would also need to be delivered to the outline group, though this group would not receive the final video.

b. Intervention Start Time

Beginning earlier in the school year would increase the likelihood that student misconceptions are attributable to the inability to transfer information as opposed to a lack of background knowledge; an earlier start date would simply reduce the amount of background knowledge required. In asking students about protein channels, for example, we assumed they already understood what a protein is and that ions and some molecules have inherent charge. If we asked those students a transfer question about protein structure, any observed misconceptions were likely to develop at the time of content delivery or iterative review. Collecting data using an early topic like protein structure would have reduced the dependence on students' previous knowledge.

Enhancing the reliability of measures of descriptive, explanatory and integrative understanding may make it more difficult to convince teachers to participate in the intervention. While test questions about later-sequence topics may be more likely to require knowledge transfer, the VA-SOL tests do not require significant depth of understanding on early-sequence topics. We might convince teachers to participate nonetheless; without repeated practice, students' retention of fundamental knowledge is low (Dunlosky et al., 2013).

Starting the intervention sequence earlier in the school year would also enable us to conduct multiple rounds of iterative review followed by a transfer assessment question. The rounds could be spaced so that materials given to participants cover early as well as later topics. If we chose to retain the protein channel topic, for example, starting earlier could mean that materials for protein structure and ions were also developed for the participants.

c. Adjustments to Materials: Transitions

Adjusting intervention materials such as sketch videos and outlines could increase the likelihood for student understanding even when background knowledge is limited or missing. An example of adjustment for the narrated sketch videos is the addition of minimalistic sketch animations (Figure 14). Simple animations could demonstrate transition states of system components.

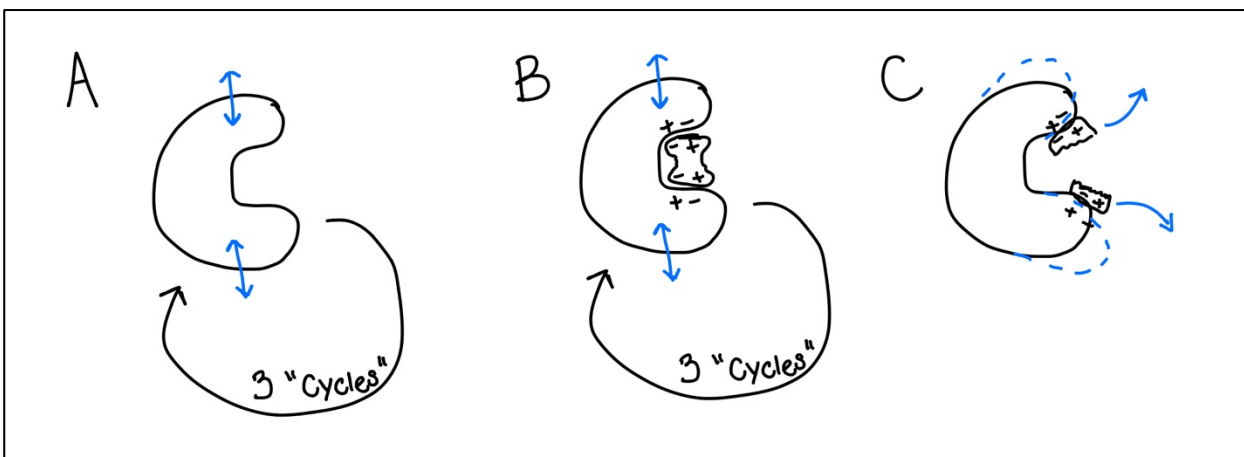


Figure 14. Possible sketch animation sequence ($A > B > C$) for the enzyme function narrated sketch video. The suggested motions (represented in blue) are minimal and simple.

Transition demonstrations have the potential to facilitate SL understanding by depicting movement in an easy-to-follow format. In its current state, the enzyme function video uses a “before” and “after” approach to describe how enzymes break apart certain substrates. The narration included in the video describes an intermediate activity: random molecular movement (RMM) causing the enzyme to stretch or bend. In the video, RMM is represented as two arrows pointing away from the opposite ends of the enzyme protein. Yet only one S1 student mentioned RMM in their answer as affecting enzyme mechanics. Other students ignored the enzyme protein stretching or attributed the stretching to electrical charges on the substrate molecule. An animation would show the substrate molecule being held when the enzyme was shifting slightly, but split apart when the enzyme was bombarded by surrounding molecules through RMM. Animation might reinforce the significance of transition states, which are important to consider when developing explanatory and integrative understanding.

2. Summary

In our research, scoring text alone was insufficient to describe a student’s mental model, which might include words alone, images alone, both (Mayer, 2009), and potentially other

elements such as sounds (Mayer, 2009) and physical gestures (Hattie & Yates, 2014).

Developing accurate metrics of mental structures using text alone will be more difficult than we hoped, and we are investigating alternative strategies.

Assessing this project's responses through written text alone limited the detection of higher levels of understanding and MBR. But if we are encouraging students to sketch their answers to assessment questions in future studies, our materials should be adjusted so that both participant groups are likely to include drawings in their answers. One possibility would be to include textbook figures or schematics in the text outlines distributed to students, giving all participants exposure to some form of multimedia learning. Building a larger materials library could allow for greater flexibility within the boundary conditions we communicate to teachers. A larger materials library would enable us to introduce students to a topic with a sequence of videos before separating them into treatment groups; we could also incorporate movement and transitions between states in these videos for increased clarity.

3. Future Plans

We intend to revise the materials presented in this thesis before launching a new pilot or full study. To accomplish this, we will need a wider network of participating schools and teachers. Our future research on sketching and drawing will continue to assess potential applications such as recall and SL understanding, in addition to gains in understanding that are descriptive, explanatory and integrative.

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Appendix A. Participant Instructions

Research Study Instructions

Hello, participants! Each student who turned in a signed consent form will be randomly assigned to one of two groups; these will be named **Group A** and **Group B**. Based on the group you are in, you will either be watching a video and sketching, or reading over a text outline of the first topic. You will do this at least **three times** on three **different** days prior to your test. For the second topic, you will be using the other method.

	Topic 1:	Topic 2:
Group A	Video and Sketching	Text Outline
Group B	Text Outline	Video and Sketching

Video/Sketching Specific Instructions:

- Your group will be given a link to a video on YouTube.
- Watch this video at least once. In the video, you will see several sketches of the topic.
- Using the *Sketch Data Collection Sheet*, copy the main sketch or create your own version. It can be as simplified as you would like, as long you understand it. You may also include the quick sketches in the start of the video, but these are not required.
 - As long as the sketch represents the topic, its quality may be of any degree. Drawing skill is not necessary!
- Be sure to include your identification code, the date, and the time it took you to make the sketch at the top of the sheet.
- Turn in at least three of these sheets (completed on *three different days*) to your instructor. You are not required to watch the video more than once, and you can reference previous drawings. If you do either of these, however, please note this in the questions at the bottom.
- If you practice the sketch more than three times, please turn in additional sheets.

Text Outline Specific Instructions:

- Your group will be provided with an outline of the topic (text only).
- Read over the outline three separate times (“sessions”) on different days prior to data collection. Take your time, but only read through this outline once per session.
- For each session, record the length of time you spent reading on the *Data Collection Sheet*. If you have more than three sessions, make additional entries.
- Turn in the log to your instructor prior to the day of your test.

It is critical that you do **NOT** share your materials from the research study with members of the opposite group. No group member should have access to both the video and the text outline for a single topic. Everyone will receive a video link for one of the topics and an outline for the other. To maintain anonymity, please do not write your name (or any other identifying information besides your study code) on the data collection sheets. You are allowed to refuse to participate at any time during the study. Thank you again for your participation in this research.

Appendix B. Sketch Data Collection Sheet

TOPIC: (1) or (2) GROUP: (A) or (B)

1. **Participant Identification Code:** _____ (First 3 letters of closest female relative's first name, last 2 digits of phone number, first 3 letters of closest male relative's first name)

2. **Time to Complete Sketch:** _____ Minutes, _____ Seconds

3. **Date:** ____/____/____

Practice Sketch # _____
(Three sketches on three separate data collection sheets are requested.)

4. Did you watch the video **immediately before** or **while making** the sketch above? YES NO

5. Did you reference any other practice sketches while drawing this one? If yes, include its number.

*Please return all three sketch pages for this topic to your instructor once complete.
 If you practiced the sketch more than three times, please return the additional practice sheets to your instructor.*

Appendix C. Outline Data Collection Sheet

TOPIC: (1) or (2) GROUP: (A) or (B)

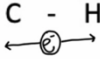
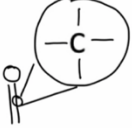
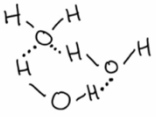
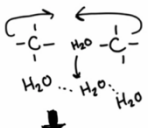
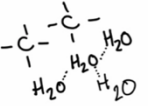
Participant Identification Code: _____ (First three letters of mother's/closest female relative's first name, last two digits of phone number, first three letters of father's/closest male relative's first name)

Session:	Date Completed:	Time:	Comments (Optional):
1		_____ Minutes, _____ Seconds	
2		_____ Minutes, _____ Seconds	
3		_____ Minutes, _____ Seconds	
Additional Sessions: *optional*	4: _____	_____ Minutes, _____ Seconds	If you complete more additional sessions, please record them on the back of this sheet.
	5: _____	_____ Minutes, _____ Seconds	

Please return this table to your instructor when complete.

Appendix D. Altered Protocol Materials for S3

1. MSFL Data Collection Sheet

MSFL Data Collection Sheet - The Hydrophobic Effect Participant ID: _____ (1 st 3 letters female, last 2 digits phone, 1 st 3 letters male) Date: _____ Start time: _____ End time: _____ (Visual Review Start Time: _____ Vis. Review End Time: _____)					
Nonpolar					
Hydrophobic Molecule					
Hydrogen Bonding					
Water molecules between hydrophobic molecules	 				

2. Non-MSFL Group Data Collection Sheet

	Session 1	Session 2	Session 3
Date			
Start Time			
End Time			
Study Method Used			
Description of Method:			

3. Hydrophobic Effect Intervention Assessment Question

Study Code: _____

Participant Assessment: The Hydrophobic Effect

Instructions for Participants: Please work through the problem below in **any** way you choose. It doesn't matter which group you were assigned to; you can answer using words, drawings, or a combination of both. If you choose to draw, however, you **must** also have your answer in words somewhere on the page. Please do not erase your work and answer on this side of the page only.

Question: Imagine you put two different neutral, nonpolar, and hydrophobic compounds (N1 and N2) into water at the same time. What would you predict to happen? If attractive forces are present, please describe them. Also include in your answer where N1 molecules and N2 molecules would be located relative to one another.

Appendix E. Additional Results

1. Pre-Survey Additional Results

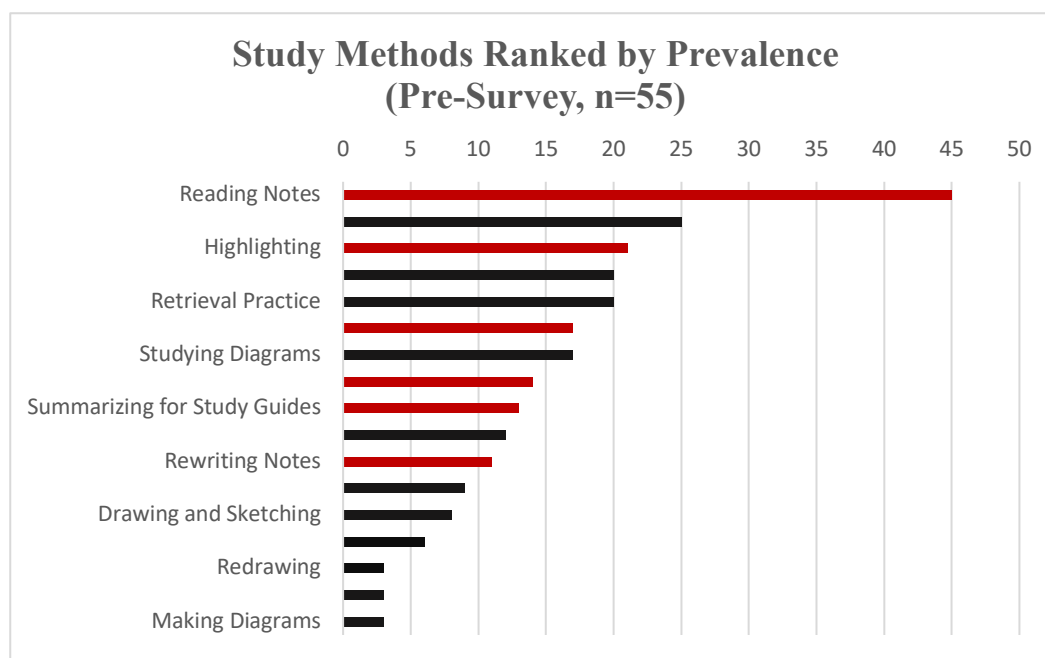


Figure A. Study methods used displayed by the greatest number of students to the least number of students. Red bars represent passive methods while the gray bars represent active methods; the lowest six methods are all active.

In addition to questions about the study methods used by participants, the pre-survey also requested that respondents provide their interest level (0-100) in science courses in general as well as the level of difficulty (0-100) experienced in these classes. In this sample, interest and difficulty levels were not correlated (Figure B).

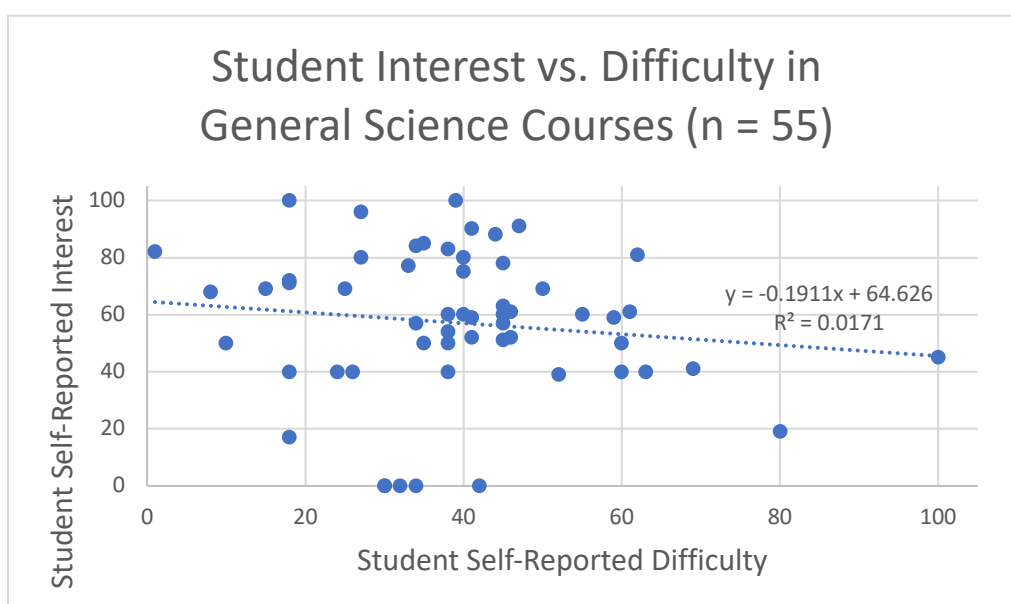


Figure B. Student self-reported interest vs. difficulty level for typical science courses.

After students identified each study method used in science courses, “carry forward” logic presented the students with a personalized list including only the methods they selected. With this list, respondents were asked to estimate the percentage of studying time they spend using each. If the student indicated that they did not study (n=4), this question was not shown. Of the study methods self-reported by students, the largest average percentage of time was devoted to reading over their notes (39.5%). The next three preferred methods by comparison were each used for an average of 24-26% of study time.

The averages of the number of passive and active methods used by the students were roughly equivalent; 2.2 and 2.3 respectively. Some students only used active or passive methods exclusively, which may have affected these averages.

Nearly two-thirds (64%) of student respondents agreed or strongly agreed that their current study methods work for them for the purpose of the introductory biology course (Figure C). A follow-up question on the pre-survey asked respondents if they matched their study methods to the material they were studying. Seven students disagreed or disagreed strongly to matching methods and material. Of these students, all but one had agreed or strongly agreed that their study methods worked for them. The majority of students (n=31) nonetheless responded that they matched the study methods used to the content covered.

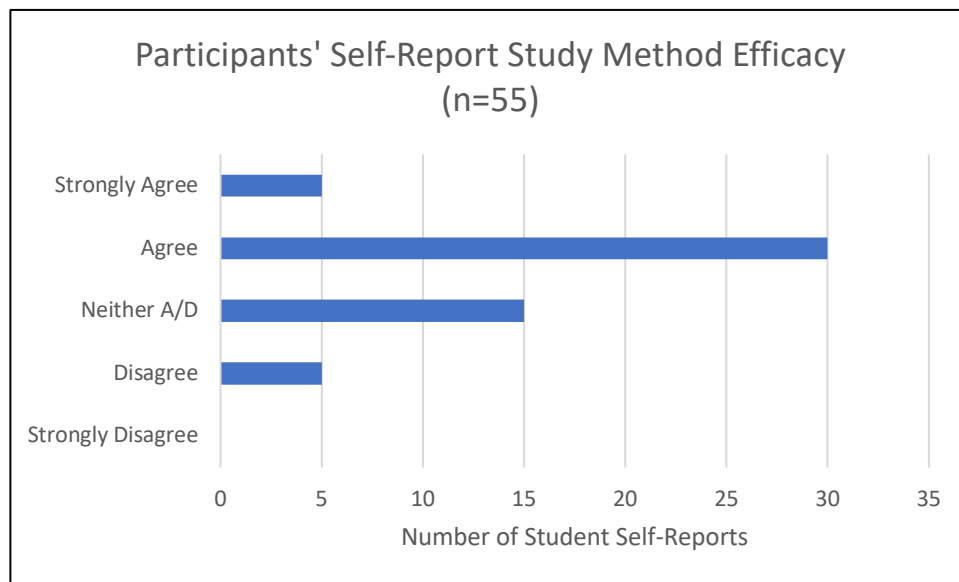


Figure C. Student responses to a pre-survey question that asked whether their current study methods work for them within the context of their current biology course.

2. Potential Change in the Assessment Question About the Cell Cycle

After reviewing the S2 responses to the transfer question about the cell cycle, we realized that the wording of the question might have been unclear. Based on the sentence structure, the agent that blocks proteins causing cell death could have been identified as the cell culture rather than the added drug. A proposed edit to the question is seen in Table A.

Cell Cycle Transfer Question Given:	Edited Version to Increase Clarity:
<i>A drug is added to a cell culture that blocks proteins that cause cell death. How would this affect a cell with no DNA damage? What about a cell with significant DNA damage?</i>	<i>A drug is added to a cell that blocks proteins causing cell death. How would a cell with no DNA damage be affected? What about a cell with significant DNA damage?</i>

Table A. Question given to S2 participants compared to proposed edits.

Appendix F. Keywords Used to Measure Structural/Descriptive Understanding

Protein Channel	Enzyme Function	Cell Scaling	Cell Cycle
<ul style="list-style-type: none"> • Specific ions/molecules • Passive movement • Membrane • Pass/move through • Match • Size • Opening • Charge distribution/gradient 	<ul style="list-style-type: none"> • Break/split bonds • Shape • Fit • Charge • Reversal • Reaction • Random molecular motion/force • Stretch/pull 	<ul style="list-style-type: none"> • Body Size • Volume • Area • Mass/Weight • Support • Distribute • Proportional • Cross-Section 	<ul style="list-style-type: none"> • Growth Phase(s) • Synthesis • Duplication • Cell Cycle • Checkpoint • Cell Death • Harsh/bad conditions

Appendix G. Cell Cycle Text Outline

Cell Cycle Text Outline

Group A

- Cell must grow and accumulate materials so that it's large enough to split into two genetically identical daughter cells that are the same size or about the same size
- First Growth Phase ("G1"): cell gets larger
- Synthesis Phase ("S" Phase): once the cell is large enough it starts to copy its DNA
- Second Growth Phase ("G2"): after duplication of DNA, cell must undergo additional growth to be ready for division (needs proteins/materials to split chromosomes)
- During mitosis, each chromosome copy will be attached to a protein strand and pulled to opposite sides of the cell
 - Wind up with two daughter cells, each has one copy of each chromosome
- It's important that damaged cells don't go through the cell cycle
 - Daughter cells may not be able to function or could become cancerous
 - Checkpoints on the cell cycle stop the process if this is the case
- DNA Damage Checkpoints: proteins in the cell can bind to damaged DNA and stop the cell cycle at that point, allowing time for other proteins to attach and repair DNA
 - Over time, if the cell can't repair enough of the DNA, the cell will die
 - Locations of DNA Damage Checkpoints: after the G1 phase, in the middle of the synthesis phase (to check for errors made while copying DNA on the chromosomes), and another during G2
- Just after the third DNA Damage Checkpoint, there is another checkpoint that makes sure that DNA replication has been completed properly
 - If not, the cell cycle will stop
- The next checkpoint is at the end of the G2 phase, called the Antephase Checkpoint
 - After replication DNA condenses and coils into thicker and thicker strands
 - Antephase checkpoint ensures that conditions are acceptable for mitosis
 - If it's too cold or other harsh conditions present, the cell cycle will stop and won't continue until those conditions have become acceptable
- Spindle Assembly Checkpoint: the last checkpoint; occurs during mitosis at the stage where the chromosomes have paired up along the middle of the cell
 - The check is to make sure the spindle fibers have attached to each chromosome
 - If any of the chromosomes don't have a protein strand attached to them that goes properly to the end of the cell, then the cell cycle will stop until all the chromosomes are properly matched up
- After passing the last checkpoint, the cell can complete mitosis, resulting in 2 independent daughter cells which may go on to function or may themselves go on through the cell cycle

Appendix H. Cell Scaling Text Outline

Cell Scaling Text Outline

Group B

- Cells of animals are mostly about the same size
 - One of your muscle cells is about the same size as one of an elephant's, a mouse's, or a worm's muscle cells
- Body sizes of animals differ a lot, which affect many aspects of structure and function
 - Allometry is the relationship between body size and function
- Imagine an animal in the shape of a cube with four legs in the shape of smaller cubes
 - Each leg must support one-fourth of the animal's mass
 - The volume of the body (larger cube) is 1 (1 x 1 x 1), and for this example we will say that volume = mass, so the mass is also 1
 - Let's say that the animal then gets two times larger in every dimension
 - Two times wider (top is now double the area) and two times taller
 - The new volume and mass are equal to 8
- If the animal is twice as large in every dimension, we must consider what happens to the legs as well
 - The legs also have 8 times the mass when doubled in every dimension, but each of the legs must still support a quarter (1/4th) of the mass
 - But even though they are 8x more massive, some of the additional cubes are stacked
 - The cubes at the top are the ones required to support one fourth of the mass
 - The mass has gotten 8x larger, but the legs have only gotten 4x larger in cross-section
- By making the animal twice as large in every dimension, we've increased the volume and mass by a factor of 8, but the legs are only 4 times larger cross-sectionally
 - A larger animal must have legs that are proportionately larger in cross-section

Appendix I. Enzyme Function Text Outline

Enzymes: Text Outline Group A

- Enzymes have some distribution of charges on the inside
 - These charges could be +1 or -1
 - The charges are more likely to be weak charges that result from hydrogen bonding
- Molecules must have the right shape and matching charges to fit into the enzyme
 - These molecules are called substrates
- Random molecular motion moves the enzyme back and forth while the substrate molecule is bound
 - This movement causes the enzyme to stretch
 - Due to the stretching, force is put on the matching charges between the enzyme and either side of the substrate
 - If the force is strong enough, it can pull the substrate molecule apart by breaking a bond that holds the molecule together
 - The result is two products that came from a single initial substrate
 - The products are able to leave the enzyme
- For enzymes that function at normal body temperature within an animal, the reactions can go in both directions
- Reversal of reaction direction:
 - Two substrates bind to the enzyme
 - The enzyme's normal flexing inward when it is in its open state can push the two substrates together
 - If the two substrates fit tightly enough, it is possible to form a new bond between them
 - If a bond is formed, you have a single product from two substrates (the reaction has gone in the opposite direction)

Appendix J. Protein Channels Text Outline

Protein Channels: Text Outline Group B

- Protein channels move ions and other molecules across membranes
- Channels have an opening through the middle for molecules to pass through
 - There is a distribution of charge at places throughout the channel that match the charges on the molecule
- In the case of water, the slight negative charge on the oxygen and the slight positive charges on the two hydrogens allows water molecules to fit very precisely in the channel
 - Water moves through the channel (called an aquaporin) passively
 - Other molecules that do not match the size and charge distribution will not pass through
 - Water will move through the channel until the number of water molecules encountering and going through the channel on one side is matched by the number of water molecules encountering and moving through from the other side
- The net movement of water through an aquaporin depends upon how many water molecules are bouncing around inside and outside
 - If nothing is attracting the water molecules inside and outside any differently, then the amount of water will wind up being exactly the same on the inside and the outside
 - If molecules on the inside attract water, such as charged or polar molecules, then some water molecules on the inside are not free to move
 - Results in the net movement of water inside
- Many channels are for specific ions (sodium/potassium/calcium/chloride)
 - There is a stronger distribution of charge inside the channel to match the specific ion the channel is designed for
 - Ions also move passively in either direction
 - Net movement of ions (whether more happen to be moving to the inside or the outside) depends upon the charge gradient present