Spring 2019

The Use of Visualizations in a Biology Classroom at the University of Colorado at Boulder as an Alternative Way to Access Student Understanding

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The Use of Visualizations in a Biology Classroom at the University of Colorado at Boulder as an Alternative Way to Access Student Understanding

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A thesis submitted to the University of Colorado at Boulder
In partial fulfillment Of the requirements to receive Honors designation in Evolutionary Biology & Ecology
May 2019

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Abstract

As educational practices start to focus on three-dimensional (3D) learning for students by incorporating practices, concepts, and core ideas, it is vital to understand how alternative forms of idea development affect student understanding. In a revolutionary 2015 commentary, Quillin and Thomas (2015) created the model Drawing-to-Learn to convey the need for drawing in Biology classrooms. The main conclusion was that since other STEM (Science, Technology, Engineering, and Mathematical) disciplines are using drawings to create a deeper understanding of the topic, there is also a need for it in biology. Using similar ideas to the concept of Drawing-to-Learn, 109 students in an upper-division Evolution class were subjects to using Visualization as a tool to communicate their ideas. In this research a Visualization was a student-produced piece of work that included multiple images, drawings, and structures to communicate their ideas about a topic and to depict prior research methodologies.

Students’ work was evaluated at multiple points throughout the semester to determine completeness of their abilities to visualize and their level of expertise in visualizing a single concept. Students were also surveyed and interviewed to access how they perceived this form of learning. No significant trends were seen in students' ability to produce expert level work between the start and end of the semester. This could be due to the relatively small sample size of a hundred students and the fact that student retention of class content was not being quantified. More research needs to be done on the effects of practice with Visualizations on student retention of content. However, there was a trend indicating that students were more complete in their abilities to visualize by the end of the semester. The survey and interview data indicated that most students found Visualizations helpful in formalizing their ideas and visualizing concepts in their own way. Visualizations could thus be used as a tool in biology class environments for STEM students to convey their level of understanding.

Key terms: Visualization, STEM Education, Biology Education, Higher Education, Evolution, Instructional Improvement, student learning, teaching methods.
Acknowledgments

I would like to thank my thesis advisor, Dr. Andy Martin, for taking me under his wings and working through the struggles of Biological Education research with me. Without his guidance and support this thesis would not have been possible. His passion for Biological Education has inspired me countless times and encourages me to continue to make STEM more accessible to students. He inspires me to change the world through my own classroom. I would also like to acknowledge Dr. Barbara Demmig-Adams, for without her guidance and feedback on creating this project I would have been lost and overwhelmed. Her reassuring support inspired confidence in this project. Finally, I would like to thank my final committee member, Dr. Nancy Guild. Her inspirational outlook on education has encouraged me to pursue my own career in the educational field. Thank you all for helping me through my process.

I am also grateful to all my friends and family who listened and supported me through this project. I am especially thankful to my mother Dr. Kathy Moore, who always picked up the phone to hear me discuss my project. Lastly, I would like to acknowledge the boundless support of my partner Will Sherman, who has constantly supported me and my educational interests.
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Introduction

As with most Science, Technology, Engineering, and Mathematical (STEM) fields, biology requires the individual to think beyond the printed words on a page. The discipline requires individuals to visualize concepts, model environmental systems, and for research, design experiments and visualize the results. To help students problem-solve and use processing skills other than just memorization of content, Drawing-to-Learn has been a structured support (Ainsworth et al. 2011). This approach emphasizes the importance of drawing and model-based reasoning for any STEM discipline (Quillin and Thomas 2015).

Looking back to influential scientist in biology, Charles Darwin sketched his observations of nature and Rosalind Franklin used models in order to explain the structure of DNA (Franklin and Gosling 1953; Darwin 2004). The subtopic of Evolution is no different. It requires students to visualize Evolution as a whole and what microevolution looks like for a given species. Since previous studies have shown that drawing is vital to master the demands of the STEM disciplines (Schwarz et al. 2009; Quillin and Thomas 2015). Then incorporating drawing into the biology classroom is important. Visual representations offer an alternative processing skill for students (Quillin and Thomas 2015). This is supported by the American Association for the Advancement for Science (AAAS), which lists the ability to interpret and model main ideas as a core competency (Bauerle et al. 2009). This skill of Drawing-to-Learn is defined as “a learner-generated external visual representation depicting any type of content, whether structure, relationship, or process, created in static two dimensions in any medium,” (Quillin and Thomas 2015).

The approach to have students communicate through drawing is already implemented in many other disciplines. This includes physics, where free-body diagrams and two-dimensional depictions of events are used, as well as in chemistry and engineering, where bond and circuit diagrams are prevalent (Quillin and Thomas 2015). Drawing allows for increased engagement with the material, reasoning through difficult concepts, and more fluent communications with other students and scientists (Ainsworth et al. 2011). Drawing can thus change how students interact with the content of STEM fields.

The current focus of change has been initiated by the Next Generation Science Standards (NGSS), which calls for education and learning to be a three-dimensional (3D) process (NGSS Lead States 2013). This means including crosscutting ideas, such as noticing patterns, in
conjunction with using the core ideas of the content and the scientific practices, such as designing and building experiments (NGSS Lead States 2013). These new standards revolve around the concept that inquiry based learning; comprehending concepts and displaying them in a personalized way, can help students process STEM content (NGSS Lead States 2013). These proposed changes in curriculum and educational practices call for studies on how drawing impacts student performance and learning processes. This research hopes to answer questions relating to the suggestion of introducing drawing into the classroom as a way for students to process major ideas and concepts in biology.

Key Terms: Drawing or Illustration or Visualization

Drawing, illustration, and visualization are all used interchangeably in daily language. To understand what this research is looking at, a clear definition of each needs to be considered. Drawing is defined as a representation formed by sketching, or the art technique of representing an object by using lines (Inc 2004). Quillin and Thomas (2015) created their own definition, as stated above that included any “structure, relationship or process” that related to content (Quillin and Thomas 2015). In relation to this study, these definitions did not seem to completely encompass what is being asked of students. Illustration, is defined as an example or picture that helps make an idea clear or attractive (Inc 2004). This seems closer to what students are creating to represent their ideas. Visualization is defined as the process of taking internal ideas and transforming them into a visible form (Inc 2004).

Although there are many similarities between the three words used to describe a way to express thought, this research defined Visualization using all three words in mind. Mainly focusing on the definition of visualization and the thoughts provided by AAAS (2009) and Quillin and Thomas (2015), a unique definition arose. Student representation of their ideas is here defined as a Visualization, which is

A student-formed illustration that represents a key idea, or the key processes involved with explaining the naturally occurring phenomena of science, in a medium restricted to two dimensions and limited text but including multiple graphs, structures, processes, shapes, drawings, and relationships.
This definition of visualization is broad enough to allow students to choose from a variety of platforms to express their thoughts. The hope of using this self-created definition will allow students to demonstrate their understanding of a topic and model their current ideas without constraint. An example of student work is Figure 1.

![Figure 1](image.png)

Figure 1. Examples of student Visualizations from the same assignment during episode 2 of Method Visualization of this research. Students are visualizing kin selection of yeast (Ostrowski et al. 2008). Panel A is a digital Visualization. Panel B is a drawn Visualization.

Each Visualization has multiple images, drawings, and illustrations. There are different images within the Visualization that represent components of the process. For example in Panel A, there is a clock that represents time and in panel B there is a camera that represents recording the data. There is limited text in each of these Visualizations, but the main idea of this experimental design are present. In order to best quantify the work students are creating, Visualization is deemed the appropriate term for this research.
Questions
1) How can visualization be quantified, and student performance measured? How is it possible to score a creative representation of ideas?
2) Does practice using Visualizations throughout a semester lead to a change in student work?

Hypotheses
1) As students receive more information about the topic of Evolution, students will become experts in the content area which will lead to expert Visualization of the concept of Evolution.
2) When students practice using Visualizations as a tool to express their thoughts throughout the semester, the completeness of their Visualizations will increase over time.
   a. As time passes, students will express themselves with less text as they are more practiced in using images instead of words for their thoughts.
   b. As time passes, students will express themselves with more images as they are more practiced in using images instead of words for their thoughts.
Methods

The Class
The research was conducted in an upper-division Evolution class taught by Dr. Andrew Martin, a professor of Evolutionary Biology and Ecology at the University of Colorado at Boulder. Data collection operated during a semester-long course with 109 students in two class sections. Each class met three times a week for an hour, for a total of 16 weeks. While there was an associated lab, data was collected only in the lecture portion.

This class would be considered a non-traditional course. Each student sat at a round table with other students. The count per table ranged from 6-8 individuals. There were eight projectors with over sixteen different whiteboards positioned around the classroom. Each day was a mix of lecture, groupwork, clicker questions, and discussion-based worksheets. Most material was covered through readings and quizzes taken at home to gauge student understanding. Tests consisted of questions that are first taken by students individually, then taken again as a group. Each exam is weighted as 5% of students’ overall grade.

The Survey
In week eight of the class, students were given an online survey. This structured survey asked students to provide rankings on the following questions:

- I really like to draw while I’m studying because it helps me learn.
- I am confident in my ability to draw or visualize my ideas.
- I would rather use paper and pencil than computer to visualize my thoughts.
- I use visualizations in other aspects of my life.
- I would be willing to be interviewed about visualizations to help a student researcher.

Students have the option of marking Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree. These are then coded 1-5, 1 being Strongly Disagree and 5 being Strongly Agree. The last question was to gauge which students would be willing to participate in an interview for this research. This was a yes, no, maybe response.

Interviews
The students who said they are enthusiastic to participate in this research received a poll to see what times they were available during the week. Out of the individuals who responded, five individuals were chosen to participate. These individuals were picked on the basis of difference
in their responses on Visualization effort, artistic ability, and past drawings on what Evolution looks like. Students were interviewed outside of classtime for 5-10 minutes and were compensated for their time. All are recorded and transcribed (Interview Transcripts). At the start of each interview, students were told the broad topic of this research and were asked if they know what Drawing-to-Learn is. This was followed by a list of questions below:

• How much experience have you had with Drawing-to-Learn in your classes?
• How much experience on your own?
• Do you enjoy drawing in your free time?
• Do you think drawing helps improve your ability to understand and remember concepts?
• Do you enjoy using paper and pencil or virtual ways of representation?
• Can you visualize a concept of Evolution that we have talked about in class for me?
  While you are drawing, can you think aloud?

For answering the last question, paper and pencil are provided to all students who agreed to participate. Students were randomly given one of three subtopics, i.e., Natural Selection (2 students), Competition (2 students), and Genetic Drift (1 student). The Visualizations generated by students are collected (Examples).

Visualizations

Students were asked throughout the semester to visualize a variety of different concepts using two types of Visualizations, Type of Visualization of one topic (Evolution) and Research Method Visualization. Most students used similar images within their Visualizations. This reflected ideas that are presented to students in class.

Type of Visualization

• Students were asked to produce Evolution Visualizations at three episodes throughout the semester, i.e., during the first week of class, during the midterm in week 8, and during the final (Examples). Each time the same question was asked, “What does Evolution look like?” No other context or rubric was given to students. The Visualizations are graded for the class either as one or zero. If they showed evidence of effort in the form of trying to connect topics discussed in class, then they received a one in the gradebook.
Using the key definitions and ideas of what Evolution looks like, a rubric was created (Figure 2). It was based off of the ideas and concepts presented to the students in class. As the semester progressed, ideas built upon each other and by the end students were being shown the Mid-parent view of Evolution. The Mid-parent perception of Evolution is the most advanced, it shows how offspring can only have traits that are the sum of their parent’s traits. It also indicates mutations, death and does not show a linear progression of a trait.

This was used to help guide the research and create consistency between scoring different students. The students never saw the rubric, but they saw each way to represent or draw Evolution throughout the semester. Sometimes a Visualization includes a variety of drawings covering Evolution, sometimes there was just one drawing. One example of student work is Figure 3. This comes from Episode three of data collection. It shows a fish population changing over time after a mutation is introduced into a population. In this Visualization there are multiple drawings: the fish population itself, the mutation shown as a chromosome, and the limited resources shown as food (Figure 3). This would be considered a score of 1 on the rubric (Figure 2) because it shows Evolution in a progressive light and indicates that Evolution is goal oriented. Although showing a more advanced ideas of death and mutation, the trait change is still very linear.
With this Evolutionary Category, a progressive Visualization would be similar to Figure 3 and represents a direct or linear path of Evolution. This would be a goal-oriented view of Evolution and is considered a novice Visualization. A score of 5 would be the Mid-Parent view of Evolution. An example of this is Figure 4. Every offspring are the sum of the parents. Sometimes there is a mutation, but there is still breeding between individuals who have the mutation and those who do not. It is not until they are their own species that they do not mate anymore. This is the most accurate and advanced view of Evolution; it would be considered an expert Visualization.

Data was collected for each student for three different episodes, looking specifically at how they visualize Evolution as a concept. Each score ranges from a Novice perspective of Evolution to an Expert perspective of Evolution. A linear model was then be applied and analyzed for this set of data to determine if there is a linear increase in the expert level of the Visualizations (Examples).
Research Method Visualization

- The Method Visualizations were given at three episodes, i.e., in weeks 4, 10 and 16. Method Visualizations were administered when the students are given a homework assignment of reading a past study that influenced thinking in Evolutionary biology (Examples). The research papers they read dealt with were: Genetic Drift, Mutation Effects, and Kin Selection (Buri 1956; Wloch et al. 2001; Ostrowski et al. 2008). Included in the description for the readings, were instructions to create a Visualization with the key points of the study’s methodology. The criteria was outlined for the students, but it was their choice on how to present the scientist’s work. Each of the key points, was assigned as absent or present and recorded as a 0 or 1. Using these values, each student was assigned an overall completeness score out of 6. In addition to collecting specific data about each experiment, the following characteristics were also collected: the Type of Visualization, Organism Shape, the Amount of Text and the Number of Images, and the Attractiveness of the Visualization as based on the grader’s perspective (Figure 5).

<table>
<thead>
<tr>
<th>Visualization Type</th>
<th>Organism Type</th>
<th>Text</th>
<th>Number of independent drawings</th>
<th>Visually Attractive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital = 0</td>
<td>Shape = 0</td>
<td>No text = 0</td>
<td>No = 0</td>
<td></td>
</tr>
<tr>
<td>Drawn = 1</td>
<td>Authentic = 1</td>
<td>Little text = 1</td>
<td>Yes = 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle = 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lots of text = 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Rubric for characteristics of the Method Visualizations. Used to record characteristics of each Visualization to offer insight into student work.

The characteristics were originally for personal interest for both the professor and researcher but offer insights into student’s work. Visualization type focused on the format of the Visualization, digital being any work that used a computer to create. Organism type revolved around the students actually drawing the organism or if they use a shape to represent it. Text was categorically based on graders perspective, but number of individual images is an exact count.

Along with the characteristics of the Method Visualizations, completeness was calculated based on the specific key ideas that came from each study.

- Genetic Drift Method Visualization was based on Peter Buri’s experiment (1956). This experiment was influential in Evolutionary Biology because he replicated
Genetic Drift in *Drosophila* (fruit flies) in a lab. It started with 8 males and 8 females that were heterozygous for a trait. From the offspring, he randomly picked 8 new males and 8 new females and mated them, then did the same thing with the offspring for over 20 generations. Buri did this with 107 different populations. He was able to show that there were two categories of flies at the end: flies who had two copies of the allele and flies that had no copies (Buri 1956). This was the first time that someone had been able to replicate this natural phenomenon in a lab. For this assignment, students were given the key ideas which are as follow:

- Evidence of reproduction
- Initial conditions of eight male and female flies
- Random sampling of eight males and females
- Counting the number of alleles at the end of the experiment
- Evidence of 20 generations of flies
- Evidence of 107 different populations of flies

Students were given the experimental paper, the key ideas, and asked to visualize the experiment while including representation for the above criteria (Appendix A). If the student included a drawing of each of the key ideas, then they received a completeness score of 6. For each one they did not indicate, they were marked down a point.

1. Mutation Effect Method Visualization was based on the experiment on yeast by Wloch et al. (2001). In this experiment, yeast cells were divided into two groups. One group, the control was left to grow, while the experimental group was treated with a chemical mutagen and then left to grow. Two cells were randomly picked from each group and left to grow on a different plate. Wloch then measured the diameter of the experimental colony and compared to the control colony. This was how fitness was measured (Wloch et al. 2001). For this assignment, students were given the key ideas as follow:

- Mutants and control being tested
- Random sampling of the yeast
- Length of time of the experiment
Students were given the experimental paper, the key ideas, and asked to visualize the experiment while including representation for the above criteria (Appendix B). If the student included a drawing of each of the key ideas, then they received a completeness score of 6. For each one they did not indicate, they were marked down a point.

- Kin Selection Method Visualization was based on the experiment of social behaviors of cells by Ostrowaski et al. (2008). In this experiment, slime molds were separated and labeled with either green fluorescent protein (GFP) or DsRed. Strains were then crossed with each other and left to grow. Pictures were taken of each cross using a fluorescent microscope. Then the fruiting bodies of the spores were collected, counted, and the percent of GFP was calculated (Ostrowski et al. 2008). This experiment showed the social behaviors of organisms and how strains of slime molds prefer their own kin to those of others. For this assignment, students were given the key ideas which are as follow:
  - Evidence of different strains of slime molds
  - Control and treatment groups
  - Evidence of the different color of dye
  - Random sampling of spores from strains
  - Documentation of results (photographs)
  - Qualification of results (counting cells)

Students were given the experimental paper, the key ideas, and asked to visualize the experiment while including representation for the above criteria (Appendix C). If the student included a drawing of each of the key ideas, then they received a completeness score of 6. For each one they did not indicate, they were marked down a point.

An example of scoring for completeness and characteristics is shown in Figure 6. This is an example of the Effects of Mutations Method Visualization. The student received a score of 5 for completeness because it is missing a drawing of 25 generations. In terms of the
characteristics, it is drawn and shows a shape as the yeast. It has some text, mainly labels, 12 images, and is visually appealing (Figure 6).

Figure 6. Student example of Mutation Effect Method Visualization. This Visualization receives a score of 5. The characteristics are scored as drawn, shape as organism, some text, 12 images, and visually appealing.

The data was collected from each episode of Method Visualizations and plotted. A linear model was then applied to the data to analyze the possibility of a linear increase in the Completeness score a Kruskal-Wallis rank sum test was also run. The Amount of Text and Number of Images are also analyzed for this data. A linear model is applied to the Amount of Text to analyze any linear trends in the data. And an anova test was run on the Number of Images to compare the means between the different episodes.
Results

Type of Visualization

Figure 7. Type of Visualization indicating level of expertise in content area for each episode. Each episode is designated by a different color, light blue represents Episode 1, turquoise is Episode 2, and dark blue represents Episode 3. Through each episode there is no distinct increase. Standard error is 4.88\(=.16\) and \(R^2\) is .526. This data produces a \(p\)-value of 1.79\(=.6\). The \(t\)-value for this data is 5.50.

Figure 8. Type of Visualization Medians per Episode. The medians of each episode was calculated and graphed here. The \(p\)-value is 0.787 and the \(R^2\) value is 0.11.
As a result of this study, there is no distinguishable difference between the three episodes of data collection. A designation of a one indicated the most novice level of Visualizations and a five indicated the most expert level of Visualizations of Evolution (Examples). There is a visual increase in the number of students producing an expert level Visualization by Episode three (Figure 7) and the median data show a higher median (Figure 8). There is also the exact same number of students producing novice work in Episode one and three. Based on the t-value (Figure 7), the null hypothesis that students would not change level of competency over episodes cannot be rejected (Hypothesis 1). The $R^2$ value indicates that 52.6% of the variation in scores can be explained by the variation in episode (Figure 7). The $R^2$ value of 0.11 indicates that 11% of the variation in medians can be explained by the variation in episode (Figure 8). From the Pre and Post look at the data, there is a trend of increase (Figure 9). This indicates that there is a trend suggesting that more students are able to produce expert level work by Episode three, but no statistical significance can be found.
Completeness

Figure 10. Completion of Research Method Visualization for each episode. Each episode is designated by a different color, light red represents Episode 1, red is Episode 2, and brick red is Episode 3. Each episode increased averagely by 1.31 points. Standard error is .118 and $R^2$ is .25. This data produces a $p$-value of $2.2^{-16}$. The $t$-value is 11.1.

Figure 11. Linear view of Level of Completion of Research Method Visualizations for each episode. The dark line is the trend line, while the translucent lines are each individual student. Statistics are the same, but a Kruskal-Wallis rank sum test was preformed and indicated a score of 95.16 and a $p$-value of $2.2^{-16}$. 
As each episode occurred, there is an increase in average points of the class. Maximum number of points is 6 if all aspects of the methodology is included in the Visualization (Examples). The standard error shows that 11% of the data is outside the normal distribution (Figure 10). Based on $t$-value of 11.1, the data shows to be away from the null hypothesis of $t=2$ (Figure 10). Most of the data then fits outside of the null hypothesis that there would be no increase in completeness over time. An $R^2$ value indicates that 25% of the variance in Completeness is explained by the variation in Episode (Figure 10). The $R^2$ value of 1 indicates that the data is a perfect fit between the variation in Median and the variation in Episode (Figure 12). The a Kruskal-Wallis rank sum test indicates a score of 95.16 which indicates a strong positive trend (Figure 11). All this indicates a strong positive trend that time effects the level of students’ ability to produce complete visual representations of Research Methodologies.
Amount of Text in Visualizations

Figure 13. Categorical quantification of Amount of Text per Visualization for each student in each episode. Each episode is designated by a different color, light green is Episode 1, green represents Episode 2, and dark green is Episode 3. There is a slight increase in amount of text used per episode (2.47 points). Standard error is 0.00164 and $R^2$ is 0.127. The $p$-value for this data is 0.172 and the $t$-value is 0.15.

Figure 14. Medians of Amount of Text per Visualization for each episode. $R^2$ value for this data is $7.4^{32}$ and the $p$-value is 1. The Standard Error is 0.57.
Amount of text used in each visualization is quantified on a scale from zero to three, ranging from no text to mostly or all text. There is an increase in the amount of text used between episode 1 and episode 2 but then decreases back to 1 in episode 3 (Figure 14). Using the $R^2$ value, 12.7% of the variation of the Amount of Text is explained by the variation in episode (Figure 13). Based on the t-value of 0.15, the null hypothesis that amount of text would stay the same cannot be rejected (Hypothesis 2a) (Figure 13). The data and model suggest there is no trend and no statistical significance can be found.

**Number of Images per Visualization**

![Box plot showing number of images per visualization](image)

Figure 15. Numerical counts of images per student Visualization over three episodes. A linear model indicates an increase in number if images (2.85 images) per episode. The data has a $p$-value of 1.15 $^6$ and a $t$-value of 4.98. Standard error is 0.572 an $R^2$ is 0.082. Anova test indicates the mean of Episode 2 is different from Episode 1 by -6.34 images and Episode 3 is different from Episode 1 by 5.72 images. Episode 3 is different from Episode 2 by 12.1 images.

Based on the statistical tests, there is an increase in the number of images used per episode. With the $R^2$ value, it can be said that 8.2% of the variation in Number of Images is explained by the variation in the episodes. The $t$-value of 4.98 shows some diversion from the null hypothesis of no change in Number of Images over the three episodes. Overall the null
hypothesis cannot be rejected (Hypothesis 2b). The anova test indicates there is a large
difference in means between each episode, but the variation in each overlap’s other episodes.
The data indicates a trend in the increase of images used over time, but no statistical significance
can be found.

**Interviews**

Five students were interviewed during the last five weeks of the semester. Four out of the
five students said that they like to draw in their free time. Most mentioned that if they had more
time in life, then they would spend more time drawing. Overall, it is seen as mainly a side
project or activity. One student mentioned that “I would enjoy it more, if I was good at it!”

A different combination of four students also thought that drawing concepts helped them
learn and remember the material of class. The one student who did not mention this, said “I
could see how it could help but I haven’t put a lot of thought into whether it helps me learn or
not.” The other four students said that they can point to specific moments where it helped them
learn. Students mentioned being able to see how everything is connected or being able to
remember what the page looked like, helps them remember the concepts. One student says that it
forces them to look into the details of methodologies, which is something they did not do before.
Another student specifically states, “I’m not sure if it would have helped me more on the exams
but in terms of retaining the information, drawing has helped me more than pure memorization.”

![Figure 16](image_url)

Figure 16. Individual competency of the five interviewed students for each episode. From statistical
analysis, there is an increase in competency (0.700 points) over the three episodes. The standard error is 0.580 and the $R^2$ value is 0.107. The $p$-value for this data is 0.253 and the $t$-value is 1.2.
This data shows that there is an increase in competency for some of the students but not all of the five sampled students. From the analysis, 10.7% of the variation is explained by the data. The null hypothesis that student competency will not change over time (Hypothesis 1), cannot be rejected based on the $t$-value of 1.2.

*Surveys*

![Graphs showing survey results](image)

Figure 17. Results from survey data from 109 students in week 8 of the semester. Each graph shows the student responses to the survey questions. None of the graphs show a normalized distribution. Most are weighted towards the Agree and Strongly Agree ends of the graphs.

These survey results show that by week eight, most students thought that the Visualizations used in class and for homework are generally useful in helping them remember the concepts. When students are asked if drawing helps them learn, over 28% of students agreed that it works. The data is distributed over a larger range of answers an about 20% of students said they disagree with the statement. Over 36% of the students surveyed said that they felt confident in their abilities to draw. Although the data is widely distributed, the largest category is Agree. There are less than ten students (9%) who disagreed that they found visualizations useful in other aspects of life. Over 80% of the students surveyed agreed that drawing out concepts is useful in other areas of life.
Summary

Overall, there is large variation in each category of results. Although there are indications of trends in the data, most results cannot be purely explained by the variables. Other factors must be at play that help explain the results seen above. Some of the trends include an increase in competency of Type of Visualization over the three episodes and overall Completeness of Research Method Visualizations over time (Figures 8, 9 and Figures 10, 11, 12). There was also indication of an increase in the Number of Images used per episode in student Visualizations (Figure 15). Interestingly there was no trend in the Amount of Text over each episode (Figure 14). All these trends are seen visually and there is no indication of statistical significance for any result. The only clear and statistically significant trend was the Completeness of student’s work over time, this indicates that students were able to complete a fuller visualization by episode three (Figures 10, 11, 12).

Interview results showed that 80% of students interviewed found that visualizing concepts helped them learn. Although an interesting result, this is a small sample size of the population of the class. When surveying the class, most students responded with varying answers about whether drawing helped solidify concepts. Although most agreed that drawing is useful in other areas of life (Figure 17).
Discussion

Based on the ideas presented in *Drawing-to-Learn*, this research aimed to inform what effects drawing had in a Biology classroom. Although using the term Visualization as it were more relevant to this research, the ideas behind getting students to express their ideas in images remained the same to that of Quillin and Thomas (2015). Based on the common idea that “practice makes perfect” a few hypotheses arose about this research. The first major hypothesis was that over time, students would trend towards a more expert level Visualization of one topic (Evolution). As more material was presented in class, the students would work on a deeper level of the mechanics behind Evolution, which in turn would resonate as an expert level Visualization. As seen in the data, there was no statistical significance to indicate a trend towards the more expert level Type of Visualization (Figures 7, 8, 9). There was variation throughout the data, but there are a number of students producing expert level Visualizations by Episode three (Figure 7).

The second main hypothesis states that over time, students would show a more complete Visualization of methodologies. This was also based on practice that students had with the ideas of visualizing and interpreting methods for themselves. Based on the data, there was a trend of increase in Completeness throughout the three episodes (Figures 10, 11, 12). Under this hypothesis, two other factors are looked at. Amount of Text and Number of Images per Visualization was analyzed for each methodology episode. The hypothesis stated that the Amount of Text would decrease, and the Number of Images would increase over the three episodes. From the data, it can be concluded that the Number of Images both increased but are not statistically significant and the Amount of Text had no trends (Figure 14 and Figure 15). This indicates that students increase in their ideas and express them through images.

In looking at the main hypotheses, there is a large amount of variation that is not explained by the specific variables in this study. Through observing the students all semester it could be said that the students were stressed during Episode two of both Type of Visualization and Method Visualization. At University of Colorado at Boulder, these episodes occurred during what is referred to as “Midterm Season.” It is said that when studying human subjects, many factors can contribute to behavior (Brown et al. 2008). Stress of the students could be one explanation for the variation seen in between the episodes.
Another explanation of the variation in the Type of Visualization data, could be the delivery of the instructions (Figures 7, 8). Episode one and three were delivered on paper to the students, while Episode two was delivered online with a midterm. Looking at the data, the majority of students preferred using paper and pencil; students could have felt restricted in their ability to visualize the content (Figure 17). If the data from Episode two was removed from the analysis, then there will be a clear increase in ability to visualize a concept (Figure 9). This trend could also be reflected in other aspects of the data as well. Looking at only the first and last episode would indicate more of a pre/post-assessment of student work. If this result were to be the only data, it would not accurately indicate the observations of student’s ability through time. Therefore, it is important to include the data from Episode two in order to stress the idea that other factors contribute to student performance. These fluctuations show how students do not always process and learn information in a linear fashion.

Combining information from the survey and interviews, this research shows that there is a benefit to students in practicing and using Visualizations. Many students indicated that drawing out concepts helped them remember the content (Figure 17). One student even stated their interview that “in terms of retaining the information, drawing has helped me more than pure memorization.” Prior research shows that not every student learns the same way (Claxton and Murrell 1987). As seen in the data, not every student believed that drawing helped them learn (Figure 17). From this understanding, it is clear that some students may benefit from having the option to use Visualizations in the classroom.
Conclusions

Teaching is a unique profession that allows us to dive deeper into the understanding of how human beings learn. It is also highly personal for both the teacher and the students. With a new focus on three-dimensional (3D) learning in science (NGSS Lead States 2013), Visualization is a tool that can be used to help achieve a holistic classroom. It gives access to students through engagement with patterns, scales, and systems. Students have to pay close attention to the details while relating to the big picture of STEM disciplines.

Since the data was not statistically significant, it cannot be concluded that students will be accepting of Visualizations. However, as some of the first data in the biology discipline using Drawing-to-Learn guidelines, Visualizations offer possibilities to enhance the student learning environment. One appeal of this instructional tool is the variation in intensity. It can be used as a simple warm up activity to gauge student preconceptions or can be used as an assessment tool. Students can be asked to sketch a simple concept or model the conclusions from the unit. Another application is a quick evaluation of student knowledge. Without grading, teachers can evaluate where the understanding of the class is at. This informs lesson planning and areas of confusion. Visualization is a simple solution to increase student engagement and mitigate a teacher’s work load.

As the world of education changes, Visualizations integrate the creative mind into the science classroom. It brings content and practices together to represent the current knowledge of students. There is no one way to teach, but this suggestion offers an alternative for students to access the major concepts in biology.

Limitations

As this research is a case study, it has some limitations to making larger claims of significance. For instance, there was not a class that served as a designated control. At University of Colorado at Boulder, there is only a set of Evolution classes per semester. They are taught by the same person and in the same way. Asking students in a control class that is not using Visualizations during the semester would have allowed for a comparison and understanding of practice with Visualizations. It would have also offered insight into student retention of the material.
Another limitation of this research is the effects of outside influences. Students have other obligations, which can range from student to student. There are many outside factors that can contribute to student effort during an extended period of time. The goal was to link these Visualization tasks with important requirements like tests, midterms, and finals. This is to give students an incentive to do the Visualizations. With the class emphasis on a student-centered learning environment, even the tests are not worth many points for their final grades. Without further research, it is hard to tell what factors lead to student’s performance to drop in the middle of the semester.

**Recommendations**

From the initial results of this study, there are many opportunities to further investigate the effect of Visualizations in a biology classroom. Studying the effects of Visualization on retention of material is the largest suggestion moving forward. Asking content-based questions after a Visualization could offer insight into student comprehension of the material. If a control class and an experimental class were to answer the same content questions and the results showed a higher retention rate in students who visualize, then it would offer significance for the importance of using Visualization techniques in biology classrooms.

Another suggestion is to try and use Visualizations of biological concepts in secondary education and measure the effects in a similar way. Looking at the effects at all levels would create a better understanding and importance of visualizing concepts. This idea of drawing concepts is common throughout chemistry and physics, but not in biology (Quillin and Thomas 2015). If the research can show the importance, then it could lead to normalizing Visualizations in biology classrooms.
References


Appendix

Method Visualization Instructions

Appendix A

Illustrate the methods of the Buri experiment described in the reading.

Here are the details:
Buri started with 107 separate populations of fruit flies (Drosophila melanogaster). Each population was identical: there were 16 individuals and each individual was heterozygous at a particular locus for two different alleles, one of which was the bw75 allele. Importantly, there was no difference in the fitness effect of the two alleles: they were selectively equivalent. Each population was allowed to reproduce and individuals developed into adults.

Each generation, Buri started a new population from each of the 107 replicate populations with 16 randomly chosen individuals: 8 males and 8 females. Each time Buri started a new population, he recorded the frequency of the bw75 allele (and because there were only two alleles, and the frequency of both alleles sums to one, he knew the frequency of the other allele). He repeated this process of reproduction, growth and founding a new population from 16 random individuals for 20 generations.

Illustrate the experiment. Make sure the following aspects of the experiment are evident in your illustration.

- Initial conditions
- The dependent (or response) variable is identified (what is being recorded)
- The experimental manipulation is shown (what is being manipulated)
- How individuals were chosen each generation
- How many individuals were chosen each generation
- There is an indication of number of generations
- There is an indication of number of replicates
- The illustration is easy to decipher

Upload a picture of your illustration using the Rich Text Editor.

Appendix A. Genetic Drift Method Visualization homework instruction. This image is what the students were given as directions to complete the Visualizations.
Appendix B

The selective effects of mutations

Homework illustrate the methods below (modified from Woch et al. Genetics 19: 441–452). Turn in your illustration as a digital image prior to class (see due date and time). A checklist is provided to assist you. Convey as much information with a minimum of text as possible (e.g., you can use symbols, including dice for randomness, clocks for time, etc.). I ask that you do this because it forces you to think more about what is happening in the experiment.

Methods

We isolated a single yeast cell and allowed the cell to reproduce for 25 generations resulting in a population of mostly identical cells. After sufficient reproduction, one half of the cells were treated with a chemical mutagen in an amount expected to produce a single mutation in the genome and the other half of the cells were used as controls. Single cells were selected at random from the two populations and plated on growth media and allowed to grow. Cells for the treatment and control were allowed to grow for the same period of time. For both the mutagenized and control colonies, the diameter of the colony was measured to the nearest 0.1 mm. Fitness for mutagenized colonies was estimated as its size relative to the average size of the control colonies.

Illustrate your experiment in a manner in which you can submit a digital copy on one page, either as a computer-generated drawing or as a picture of a hand-drawn illustration. I can read .docx, .pdf, and .jpg files.

Checklist of necessary items for full credit
1) Picture is easy to decipher (good picture, organized, etc)
2) Control and treatment clearly distinguished
3) Time is indicated
4) Random sampling of individuals indicated
5) Measurement of size indicated
6) Fitness estimation is indicated

Appendix B. Mutation Effect Method Visualization homework instruction. This image is what the students were given as directions to complete the Visualizations.

Appendix C

Illustrate the experimental methods


We collected and isolated different strains of slime mold (*Dictyostelium discoideum*) from the wild and suspended each strain in a buffer solution so there were $6 \times 10^7$ cells/ml. For the control, we separated a single strain into two equal volumes and labeled each separate set of cells with either green fluorescent protein (GFP, a green dye) or DaRed (a red dye). For the experimental treatments, we created a series of mixtures of pairs of strains. Pairs of strains were combined in equal proportions. For each experimental treatment, we labeled one strain with GFP and the other with DaRed. The control cells and experimental mixtures were spread out onto separate petri dishes with a layer of food. The densities of cells on each petri dish for the control cells and experimental mixtures were the same. The cells were incubated and allowed to grow and develop fruiting bodies for 24 hours. The plates were photographed using a fluorescent microscope. In addition, randomly-selected fruiting bodies from each petri dish were harvested, suspended in solution, the spores counted, and the proportion of GFP spores calculated. This experiment was conducted for multiple isolates of wild slime molds.

Your job is to draw an illustration of the methods that clearly describes how to test the hypothesis that cells aggregate and form fruiting bodies depending on relatedness. Consult the rubric below for key elements of your illustration. Please use a minimum of text and be as creative as possible.
Appendix C. Kin Selection Method Visualization homework instruction. This image is what the students were given as directions to complete the Visualizations.
Appendix D. Student examples from Episode one of Type of Visualization collection. Most students had work similar to this. Most students had a progressive type of Visualization because they showed human evolution that is linear and goal-oriented action.
Appendix E. Student examples from Episode three of Type of Visualization collection. Most students had work similar to this. At this point students are showing more advance visualizations. Like seen in Panel A, there are still many students who showed a progressive Visualization that is goal-oriented. As seen in Panel B, the student visualized Evolution in three different ways, showing a progressive, a phylogenetic tree, and a Mid-parent graph. C and D show examples using the Mid-parent graph, and expert Evolution Visualization.
Appendix F. Student examples from Kin Selection Method Visualization. Panel A received a 5 for completeness, they are missing documentation. Panel B received a 4, they are missing indication of control and experiment groups and random selection of cells. Panel C received a 6 because they had all key ideas represented. Panel D received a 6 as well.
Appendix G. Student examples from Mutation Effects Method Visualization. Panel A received a 5 for completeness, they are missing record fitness. Panel B received a 5, they are missing evidence of 25 generations. Panel C received a 6 because they had all key ideas represented. Panel D received a 6 as well.
Student Examples From Interviews

Appendix J. Visualization from Interview. Student was asked to draw Genetic Drift. Student discussed ideas about the Buri experiment and tried to recreate the graph displayed in class. Transcript is Appendix M.
Appendix H. Visualization from Interview. Student was asked to draw Natural Selection. Student discussed ideas about the Industrial Revolution causing changes in moths. Progressive perspective on Evolution. Transcript is Appendix N.

Appendix I. Visualization from Interview. Student was asked to draw Natural Selection. Student discussed ideas about individuals in populations dying off after environmental pressures. Transcript is Appendix O.
Appendix K. Visualization from Interview. Student was asked to draw Struggle for Survival. Student discussed ideas about natural pressures and competition for resources with tree roots. Progressive perspective on Evolution. Transcript is Appendix P.

Appendix L. Visualization from Interview. Student was asked to draw Struggle for Survival. Student discussed ideas about limited resources for both water and mates. Discussed the idea that the stronger bear would be able to reproduce because of the strength and access to water and mates. Progressive perspective on Evolution. Transcript is Appendix Q.
Appendix M. Student transcript, student was asked to visualize Drift.

Interview Questions:

1. How much experience have you had with Drawing to Learning in your classes?
   Not, the only thing I have done is for projects. I have never had to do anything smaller like we do in this class.
   In high school I probably did more projects like that then I do now. Since they love to do those sorts of projects in high school.

2. How much experience on your own?
   Yeah, I usually do everything in my own space, I have all my different equipment.
   Yeah, I have, yeah, I like sketching, so I have a bunch of things for that. I have a bunch of pens that I use for this class. It's fun to have a bunch of different colors.
   No, I do not visualize for other classes. Sometimes I color code, but I do not draw as much for my other classes. Maybe chemistry, but that is probably it.

3. Do you enjoy drawing in your free time?
   Yeah! I do like to draw. It is not the same type as for this class. I try to do more realism when it is just myself but when I do illustrations, I try to keep it cartoony and simple. It is definitely something I like to do.
   I do it whenever it strikes me, I am not a huge art person, just something I do once and awhile.

4. Do you think drawing helps improve your ability to understanding and remember concepts?
   Definitely helps me remember stuff. It is easier for me to remember pictures. That's just the way my brain works. I think it forces me to look at details more, describing I just get the general understanding but when I go to draw, oh I am missing a few details. It helps me understand how things work. It helps me for class the next day. Having to write it down and where it goes on the page helpful.

5. Do you enjoy using paper and pencil or virtual ways of representation?
   Depends, if I had a drawing tablet I would choose that. I know that it can be easier to do digital stuff, but I think for this class, it gets too complicated to do on computer. I do it on paper and pencil, so I do not have to struggle with a program that is not doing what I want it to do. My hands will do the right thing. With a tablet and a better program I would do it online.

6. Can you visualize a concept of Evolution that we have talked about in class? (For Example: Natural selection, Drift, Variation, Heritability, Competition)?
   Draw what it looks like when ...(Drift) ... Is happening?

Draw: Drift

Normally it takes me a while to think about what I want to start with and where things should go on the page.
Well I am thinking about the fly experiment. We did illustrate it before, but I do not remember.
So I’ll show the change in genetics over time. Wow my brain doesn’t want to do this, normally I do this at night.
Okay to show what drift does, you start with a population that is heterozygous. Then you would show that over time they would go into two different directions. One gene drops out or something like that.
So I would show starting population. Heterozygous population. Then there are two populations over time.
You have multiple heterogeneous populations over time. I guess eventually, you would show the change in frequency of the allele.
I will probably think about it later and say wow I have a way better idea now.
Well it makes since because you start with a bunch of heterozygous populations and then over…
Oh I forgot you had to pick randomly to reproduce. I will draw a little dice for random. Just more populations in between then.
Just the change in alleles through random picking.
Appendix N. Student transcript, student was asked to visualize Natural Selection.

Interview Questions:

1. How much experience have you had with Drawing to Learning in your classes? Like a specific thing?
   Yeah, I have heard about it.
   It is basically what we are doing in this class.
   College classes? So in college mostly just in this class.
   In high school, yes, in humanities a couple times. Yeah, we did some drawing in high school, mostly in reading classes. Draw little boxes to show the story line.
   Concepts maps are new, in terms of us actually drawing them. I have seen them proposed in learning outcomes. Me physically creating a concept map for science is something new.

2. How much experience on your own?
   No, I’m a big list person. I am a visual learner, so it would sound like I would draw things, but I can picture my notes. Writing things out is better for me. I find that drawing things out is helpful for me as well, but I personal just write things out in lists.

3. Do you enjoy drawing in your free time?
   Drawing is something I force myself to do. I doodle sometimes but not really anymore. In college I’m not bored anymore like I was in high school. In high school I use to do doodle when I was bored. I wish I was a better drawer, but I am not a good drawer or painter, or anything physical, hand to paper contact.

4. Do you think drawing helps improve your ability to understanding and remember concepts?
   Yeah. I do find that it was easier to, well first I was like oh crap I do not even remember what we did for homework. But after I remember the six fish across the page, I kind of remembered what the rest of the page looked like. It was easier for me to remember what I had drawn. Sometimes it is hard for me to draw out experiments when I get a list. That is harder for me.

5. Do you enjoy using paper and pencil or virtual ways of representation?
   Well it depends on what he is visualizing because I use to do lot of graphic design. I am a lot better at art on my computer. But it is not so much art that I can apply to biology. It's not like I am taking clip art of fish and creating speciation. I do magazine layout. I am more confident with online art.

6. Can you visualize a concept of Evolution that we have talked about in class? (For Example: Natural selection, Drift, Variation, Heritability, Competition)?
   Draw what it looks like when ... (Natural Selection)... Is happening?

Draw: Natural Selection

Moth one with the industrial revolution because that is something they drill into your head and it is something that I know. And I can draw butterflies!
You have to come up with some short of timeline.
And then I will do the environment first, so this is a tree and another tree. At the finish we have some darker trees. And so we have some light trees and dark trees.
   At same time or different time?
At different times. So this will be pre-industrialization. This is post-industrialization.
And we have some butterflies that are white and apparently huge. They are not drawn to scale.
So these are a bunch of butterflies and we have one that is darker. This darker butterfly dies and this generation…
   Why do they die?
Well cause a bird, thanks for reminding me, that's a bird. Eats a moth because it can see it better.
Then in the next generation, well I’m just going to go the two extremes. So in this one I am drawing a bunch of darker butterflies over here. There is one light butterfly that gets eaten by this bird because it can see that one and consumes it.
So I guess I need some sort of in between period. Where one tree is darker, let's say two trees are darker but this one is lighter. There is a proportional amount of light to dark butterflies.
Yeah, there it is!

Appendix O. Student transcript, student was asked to visualize Natural Selection.

Interview Questions:
1. How much experience have you had with Drawing to Learning in your classes?
2. How much experience on your own?
3. Do you enjoy drawing in your free time?
   Yeah! Not much time spent - into project draw a lot. Typically don't have time consistently
4. Do you think drawing helps improve your ability to understand and remember concepts?
   Yes absolutely. Very visual learner. Even seeing words on paper - seeing how things are connected. How processes works allows for better recall with visual things.
5. Do you enjoy using paper and pencil or virtual ways of representation?
   Paper and pencil. Going through the motions is really helpful
6. Can you visualize a concept of Evolution that we have talked about in class? (For Example: Natural selection, Drift, Variation, Heritability, Competition)?
   Draw what it looks like when … (Natural Selection)... Is happening?

Drawing: Natural Selection

Initial thought should show population circles or something abstract
Then indicate some different symbols X or filled in to show certain traits
Then as time would pass, there would be environmental pressure
Population that would be generations down the line
More of that one trait than other

Starts drawing

Starts out with about even numbers of each trait
Then over time, one trait becomes the more dominate one because more adapted for the environment

Oh missed a step in beginning
All traits arise by random mutation - now have one filled in
Asexual reproduction and becomes more popular

Time! ( indicates with clock and then with words indicates generation)

Labels environmental pressure with words

Two questions:
What would environmental pressure look like?
   Depends on what trait talking about
   Drawings in class, species red mangroves, numbafores, snorkels,
   Environmental pressure was sea level rise, higher snorkel survived
Appendix P. Student transcript, student was asked to visualize Struggle for Survival.

Interview Questions:
1. How much experience have you had with Drawing to Learning in your classes?
   Pretty much this one only. Nothing in high school. Pretty unique for this class only, maybe here and there but nothing big.
2. How much experience on your own?
   Sometimes, I like to make maps, connect things that way. Mostly things are just in my head.
3. Do you enjoy drawing in your free time?
   I LOVE drawing in my free time and keep it as my free time activity. Pretty okay artists.
4. Do you think drawing helps improve your ability to understand and remember concepts?
   I could see how it could help but I haven’t put a lot of thought into whether it helps me learn or not. Right now it is kind of something we just do for this class. It takes a long time which can be annoying.
5. Do you enjoy using paper and pencil or virtual ways of representation?
   Paper and pencil. Computers are hard.
6. Can you visualize a concept of Evolution that we have talked about in class? (For Example: Natural selection, Drift, Variation, Heritability, Competition)?
   Draw what it looks like when …(Struggle)... Is happening?

Draw: Competition and How that relates to Evolution- Take that however you want

   So I am going to draw two different trees,
   This is the ground because we are going to draw the root systems
   Okay with these trees, they are the same species
   Here are the nutrients

And the nutrients are in the ground?

   Yeah. And this tree has roots that are kind of shallow, and this tree has roots that are pretty deep.
   And of course there is going to be a lot more of these species
   (Only drew 1 of each species)
   And then after some time, this one is dead

So the one who had shallow roots died?

   Yeah, It's super dead, because it couldn't get the nutrients
   And this one who had deep roots lived, and then it had babies
   And then all of these have deep roots and they all live
Appendix Q. Student transcript, student was asked to visualize Struggle for Survival.

Interview Questions:
1. How much experience have you had with Drawing to Learning in your classes?
   Ever since Elementary school have been drawing concept maps, didn’t care for them then. I can kind of see their importance and relevance now. But for Human anatomy my prof really stressed the importance of drawing the structures, so for human anatomy and Phys I studied by drawing out the structures. Drawing the receptors, the proteins.
   As far as drawing experiments, this was the first class that I have ever drawn out the methods for an experiment.

2. How much experience on your own?
   I do, they encourage this in physics with the Free Body diagrams. So I find myself drawing the actual diagram on my homework and on the problems to help see what is going on. I guess I don’t do that a whole lot independently.

3. Do you enjoy drawing in your free time?
   I would enjoy it if I was good at it! I’m not very good at it, I dabbled here and there when a kid. I doodle during class sometimes. Overall, I do.

4. Do you think drawing helps improve your ability to understanding and remember concepts?
   Yeah, I do. Looking back at my Human anatomy and Phys, also in micro bio I did the same thing. I’m not sure if I were to go back and not draw at all and just try to memorize it. I’m not sure if it would have helped me more on the exams or not but in terms of retaining the information, drawing has helped me more than memorization. Plus know I have all this material of drawings I can go back on.

5. Do you enjoy using paper and pencil or virtual ways of representation?
   Want to get into technology, but I can’t find a program on my mac. I would like to try that out but when we have tasks like this I normally go directly to paper and pencil.

6. Can you visualize a concept of Evolution that we have talked about in class? (For Example: Natural selection, Drift, Variation, Heritability, Competition)?
   Draw what it looks like when ...(Struggle)… Is happening?

Draw: Could you visualize competition?

   First thing I think about it negative and then a positive for the symbiotic relationship
   An example would be a competition for resources
   Oh I am so bad at drawing
   Okay so there is a bear and it’s this big and he is in the same area, with sort claws, and there is another bear of much bigger size with larger claws.
   They both want the same thing, they both want this water source, fresh body of water.
   The bigger one gets it and the smaller doesn’t

Cool I like it! Anything you want to add?

   Small bear is defeated, not dead, not what I am trying to draw
   Maybe they got into a fight over the water, or females, maybe I’ll draw some females over by the pond too. This is where the females hang out. Major competition. What’s the symbol for female?

It's the cross one.

   Okay so females over here. Lounging by the pool. These two are both males.
   Yeah, probably could have drawing a simpler better drawing but that is what I have for you.