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The Effects of Scientific Inquiry Methodologies on Student Understanding of Evolution

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Abstract

The purpose of this paper is to investigate the effects of a scientific inquiry-based curriculum on student understanding of evolution. The study involves students ages 15-17 enrolled in a general biology course at a large suburban high school in the United States. This unit uses various scientific inquiry methods, including student-led group work and technology-based virtual labs. The researcher used several data collection methods, including a pre-and post-unit assessment and student surveys. The goal was to use the data to assess student learning and student preference of inquiry activity. The results suggest that the unit successfully addressed student misconceptions regarding evolution and promoted student inquiry. The digital inquiry lab was found to be the least engaging for inquiry purposes. Further research is needed to assess other forms of inquiry using technology and how results translate when used with other biology units.

Keywords: scientific inquiry, secondary, evolution

Scientific inquiry is a teaching style, a philosophy, and a learning target for STEM students at all levels. In inquiry learning, the construction of student knowledge happens in an intensely interactive, collaborative, and authentic way (Areepattamannil, 2012). Inquiry-based learning has been shown to facilitate the development of students' investigative skills and prompts them to communicate their explanations of current phenomena using evidence (Burgh & Nichols, 2012). Pursuing scientific inquiry makes what students do in the classroom more aligned with what scientists are doing professionally (Whannell, 2018). To participate in inquiry learning is to partake in an extensive, open-ended investigation with plenty of space for failure and self-correction, which encourages the student to take ownership of the learning processes (Edelman & Edelman, 2017).

When comparing scientific inquiry to a more classical and direct teaching style, inquiry-based instruction has improved student outcomes, including on standardized tests (Whannell, 2018). Whannell (2018) also discusses how teaching science through inquiry is more engaging for students and enhances the overall understanding of scientific concepts. Inquiry-based instruction in science classes also expands the retention of science knowledge far longer than traditional lecture-based instruction, and has a positive effect on student motivation (Edelman & Edelman, 2017).

There is abundant literature supporting scientific inquiry in the classroom, yet many teachers are not embracing it. As schools shift to embrace the Next Generation Science Standards (NGSS), more research will be needed about best practices for inquiry-based pedagogy to develop new models of curriculum, instruction, and assessment. Whether or not students pursue careers in STEM, the goal of educators should be to use inquiry-based pedagogy to help students become independent thinkers who are engaged in their community (Burgh & Nichols, 2012).

A thorough review of the literature has revealed three distinct ways teachers can successfully promote scientific inquiry: in the classroom (large group and small group), using technology, and in outdoor learning. The following study aims to investigate the extent to which each strategy effectively built student scientific inquiry from the perspective of both the student and the teacher. The data yielded from this study will help determine to what extent facilitating a weekly inquiry-based investigation for four weeks can improve student scientific inquiry skills and content knowledge in a secondary science evolution unit. Secondarily, it can provide information on the relative effectiveness of each of the three different approaches to inquiry-based learning to guide future curriculum development.

Theoretical Framework

Pragmatism, as an educational theory initiated in the early 20th century, states that education should be teaching students the practical things for life in a way that encourages personal growth through experiential learning (Hickman, 1984). While our understanding of this way of teaching is heavily based on the work of William James and Charles Pierce, one of the biggest names associated with Educational Pragmatism is American philosopher and educator John Dewey (Khasawneh, 2014). His ideas have stayed at the forefront of education reform for decades and remain at the core of the current definition of scientific inquiry. To learn scientific inquiry is to engage in learning (Waks, 2009).

Teaching science pragmatically requires teachers to teach inquiry through the scientific method, not as a linear set of technical facts to be memorized (Hickman, 1984). Students are focused on learning by doing as an alternative to rote knowledge and strict teaching (Khasawneh, 2014). The activities designed for this study were developed to align with pragmatic theory in that they encourage experiential learning. Students who participate in the classroom experiences will ask novel questions, form hypotheses, and use evidence and background knowledge given in the investigation to support their hypotheses, thereby cycling through the scientific method several times to construct their content knowledge. Because the key objectives in a pragmatic education include meaning, experience and method, it is easily applicable to scientific disciplines such as biology, which is an exercise in finding what is true in the natural world through unbiased observation and experimentation. The following literature review was primarily focused on research done using inquiry to engage students in science learning.

Review of the Literature

This review of the literature will define scientific inquiry and the teacher's role in facilitating learning. There are three main strategies for teachers to successfully promote scientific inquiry: using small-group activities in the classroom, using technology-based simulations, and using an outdoor learning approach. There was an explicit limitation in finding ways to promote scientific inquiry in high schools throughout the research process. However, studies done with introductory college students can also provide helpful insight. This review will investigate the extent to which each strategy was effective at building student inquiry. It will conclude by reviewing the teachers' role in and reactions to teaching scientific inquiry, and several predominant barriers to teaching scientific inquiry are identified.

Defining Scientific Inquiry

Scientific inquiry is a teaching style, a philosophy, and a learning target for STEM students at all levels. This review defines the goals of scientific inquiry through the lens of secondary and undergraduate science teachers. Scientific inquiry as a concept has been around for over one hundred years. The person most consistently given credit in the literature is John Dewey, a progressive philosopher of education (Burgh & Nichols, 2012). He stressed that science should not be taught as facts to be memorized but as a way of thinking and doing. According to Dewey, “Learning is not the learning of things, but the meaning of things” (Burgh & Nichols, 2012, p. 1047). His ideas have stayed at the forefront of education reform for decades and remain at the core of the current definition of scientific inquiry. To learn scientific inquiry is to engage in learning. This type of learning facilitates students’ investigative skills and prompts them to communicate their explanations of current phenomena using evidence (Burgh & Nichols, 2012).

As Areepattamannil (2012) points out, inquiry-based science teaching is a form of student-centered teaching, meaning that the construction of knowledge happens in an intensely interactive, collaborative, and authentic way. Pursuing scientific inquiry makes what students do in the classroom more aligned with what scientists are doing on the job (Whannell, 2018). Rather than committing the textbook to memory, students use the knowledge provided to focus on open-ended investigations. This focus requires students to practice making observations, asking questions, consulting literature, collecting data, using tools, and piecing together explanations (Koyunlu Unlu & Dokme, 2020). What makes scientific inquiry different from the scientific method is the expectation of self-correction and the opportunity to be wrong. To participate in inquiry learning is to partake in an extensive, open-ended investigation with plenty of space for failure and self-correction, which encourages the student to take ownership of the learning processes (Edelman & Edelman, 2017).

When comparing scientific inquiry to a more classical and direct teaching style, inquiry-based instruction has been found to improve student outcomes, including on standardized tests (Whannell, 2018). The same study discusses how teaching science through inquiry is more engaging for students and enhances the overall understanding of scientific concepts. A 2017 study similarly submits that inquiry-based instruction expands science knowledge retention far longer than traditional lecture-based instruction while also positively affecting student motivation (Edelman & Edelman, 2017). Other than measuring content knowledge and student motivation, researchers have gauged the effectiveness of an inquiry-based intervention by observing student ability to determine the validity of evidence, ability to make connections between knowledge and phenomena, and overall enjoyment of an investigation (Edelman & Edelman, 2017; Gilbuena, 2012; Jin & Bierma, 2013; Walls, 2016).

Inquiry in the classroom using group activities

A common and cost-effective form of inquiry-based learning occurs in the classroom in small-group activities that focus on investigating a specific phenomenon. Jin & Bierma (2013) investigated the effects of using Process-Oriented Guided Inquiry Learning (POGIL) exercises in a class of non-STEM undergraduate students. POGIL emphasizes students' ability to analyze data and construct explanations while self-managing in learning teams (Jin & Bierma, 2013). The POGIL method was also utilized by Şen & Yilmaz (2016) in a high school science class to target inquiry while teaching electrochemistry concepts. Overall, the POGIL units appeared to be associated with an overall increase in content mastery (Jin & Bierma, 2013; Şen & Yilmaz, 2016). Daubenmire (2015) analyzed classroom interactions and student performance in general chemistry. The researchers found that students who participated in the POGIL activities scored higher in chemistry than those who did not (Daubenmire, 2015). They also found that even in an inquiry-based lesson, the instructor's style of approach with student groups is an essential determinant of how much students learn in the activity (Daubenmire, 2015).

Inquiry using technology

As was made evident in 2020 by the COVID-19 outbreak, instructing and learning in the classroom is not always an option. However, according to a few studies on promoting scientific inquiry using technology, it may be possible to develop these critical thinking skills using a computer simulation. A 2015 study involving middle and high school students found Science Classroom Inquiry (SCI) simulations to be stimulating, enjoyable, and cost-effective (Peffer, 2015). In these simulations designed to lead students in investigating scientific phenomena, students had to formulate and test novel hypotheses and think creatively to justify their choices. The scaffolding within the simulation proved to be effective: 67% of students said their view of authentic science had changed and that the simulation positively affected both student learning and understanding (Peffer, 2015).

Gilbuena (2012) investigated the effects of technology on student inquiry in high schools with lab simulations designed to mimic an authentic engineering project. This project required active engagement and student construction of knowledge (Gilbuena 2012; Peffer, 2015). Even with the focus on engineering, teachers observed positive effects on student motivation and student understanding in biology, chemistry, and physics classrooms (Gilbuena, 2012). The added benefit is that Gilbuena's (2012) simulation expanded student views about practicing engineering, a key focus of NGSS.

Walls (2016) saw gains in student knowledge (measured using identical pre- and post-activity assessments) using an investigation targeted to develop students' scientific inquiry. Students had to create hypotheses to create a plan to protect a proportion of the population in a vaccine efficacy simulation. Student motivation was notably high in Walls' study, as was reported in Gilbuena's study (Gilbuena, 2012; Walls, 2016). In all three of these studies, students were expected to fail, reflect, and self-correct at each stage of the simulation (Gilbuena, 2012; Peffer, 2015; Walls, 2016).

Taking inquiry outdoors

The final strategy to promote scientific inquiry discussed in this review occurs outside the confines of the classroom walls. Both outdoor classroom pedagogies and place-based educational philosophy have strong roots in inquiry-based teaching. A 2019 review found that bringing students outside the classroom to learn positively affects their engagement with the learning and developing their critical thinking skills (Kuo, 2019). Kinslow's 2019 study looked at a high school field-based ecology course that conducted a six-week investigation of the community ethanol plant. The choice to go with an extended investigation was due to previous findings that field-based activities, while engaging, do not statistically improve critical thinking skills (Kinslow, 2019). Students participated in bird banding and water quality analysis outdoors as a part of the Kinslow study, and the student learning logs maintained throughout showed growth in many areas, including scientific inquiry and scientific literacy.

Edelman and Edelman (2017) also found success promoting scientific inquiry while observing students outdoors in an introductory post-secondary biology course. The focus of the class was on conservation biology, and in forgoing the traditional lecture component, instructors promoted scientific inquiry by supporting student groups as they designed and executed their research projects. Utilizing camera traps, students mimicked the role of conservation biologists by performing their research outdoors on the school campus. This student-centered design had positive effects on student enthusiasm and motivation. In both studies involving outdoor learning and inquiry, students gained experience using scientific inquiry, including asking scientific questions, designing and conducting research, or collaborating within groups (Edelman & Edelman, 2017; Kinslow, 2019).

Teacher Role and Barriers

As the literature has shown in each study included in this review, teacher guidance is pivotal to a successful scientific inquiry activity. The studies included in this review perceived several constraints to teaching inquiry-based science courses. The most common barrier identified was the lack of teacher support, whether that means curriculum development workshops (Areepattamannil, 2012) or training on effective facilitation of an inquiry classroom (DiBiase & McDonald, 2015; Kali, 2018; Koyunlu Unlu & Dokme, 2020). Many teachers were skeptical on how a focus on inquiry might affect student performance: In one study, 84% of teachers expressed concern about how switching to inquiry-based teaching would affect their student's final exam scores, while 79% worried about the misuse of class time, and despite 90% of the teachers agreeing that it is a highly effective way to teach students (DiBiase & McDonald, 2015). Other studies elaborated on the barriers recognized in pursuit of this complex practice, including time to prepare lessons and the money for new classroom resources (Edelman & Edelman, 2017; DiBiase & McDonald, 2015; Gilbuena, 2012; Peffer, 2015). Technology-based investigations came with their own set of challenges, including IT infrastructure and difficulties in grading project-based online assessments (Gilbuena, 2012). Teachers pursuing the outdoor approach felt additionally limited in time and support regarding the logistics of field trips and planning for outdoor learning (Edelman & Edelman, 2017). DiBiase and McDonald (2015) highlight the need for continual professional development and time for collaboration within departments to expand the resources available to teachers regarding inquiry instruction.

Current research on promoting student scientific inquiry indicates several effective strategies when teaching science as a way of thinking, including classroom activities, technology-enabled simulations, and outdoor investigations. It is not clear whether one is more effective at promoting inquiry at this time, though it is clear that both technology and outdoor-focused approaches come with a unique set of barriers to teachers. In future research, a consensus must be reached regarding the criteria used to measure student gains in scientific inquiry, and barriers to teachers must be addressed. The pursuit of inquiry in classrooms remains incredibly important as we prepare our students to face real-world challenges. As shown in the literature review, exposure to problems through extended investigations helps create citizens who enter into society with the tools to solve our current and future problems. At the secondary level, it is clear the teacher plays an enormous role in engaging and encouraging students to construct their understanding. The value of this process cannot be understated: scientific inquiry is a skill that comes with active participation and lots of practice, and gains in student scientific inquiry will almost certainly move the needle on major global issues such as climate change. As Burgh and Nichols (2012) put it, “By engaging in the social practice of thinking together, students learn to think for themselves” (p. 1054).

Methodology

This study used an experimental design. In addition, classroom observations, teacher reflections, and an analysis of students’ work in class were leveraged in the interest of triangulation. Pre- and post-assessments were presented in the form of a formative assessment that targeted common student misunderstandings surrounding the topic of Evolution.

The population for this action research study was tenth and eleventh-grade students enrolled in a general biology course at a large suburban high school in Midwestern United States.

The sample included 28 high school students enrolled in general biology in the first trimester of the school year. All students were in the same class period. The sample featured 14 females and 14 males. The course studied was a required science credit, and the sample was representative of the high school population.

Table 1

Sample Demographics

	Males	Females
Grade 10	12	14
Grade 11	2	0

Identical pre- and post-assessments were used to gauge student understanding of evolution before and after a series of scientific inquiry activities. The 20 questions on the assessment were all multiple choice and were designed to directly address common misconceptions related to evolution. Students were given time in class to complete this assessment once on the first day of the unit and once again after all scientific inquiry activities had concluded at the end of the unit. Student engagement during the scientific inquiry activities was assessed in a variety of ways. The teacher utilized a student behavior observation chart during the activities to gauge student reaction and productivity as an observation tool. Students provided feedback on inquiry activities using an anonymous Google form used as a student inquiry feedback tool, in which they ranked the activities on several criteria. Student discussions during one specific inquiry exercise were recorded and analyzed for student participation and understanding. Finally, the teacher recorded written personal reflections after each activity. The data collected was analyzed later in the academic school year by the classroom teacher.

Analysis of Data

The raw data for this study came in a few different formats. Student assessment data was compiled in Schoology and was compiled and analyzed for 27 total students. All identifiers were removed prior to analyzing. Data was graphed to show the difference in student scores before and after the intervention. Student feedback was collected anonymously via Google Form. Data from the student behavior observation chart was graphed to show the frequency of behaviors during different activities. Finally, the simple sentences and short statements written by the teacher on the teacher log after each activity were ranked based on the teacher's perception of student engagement and understanding.

Findings

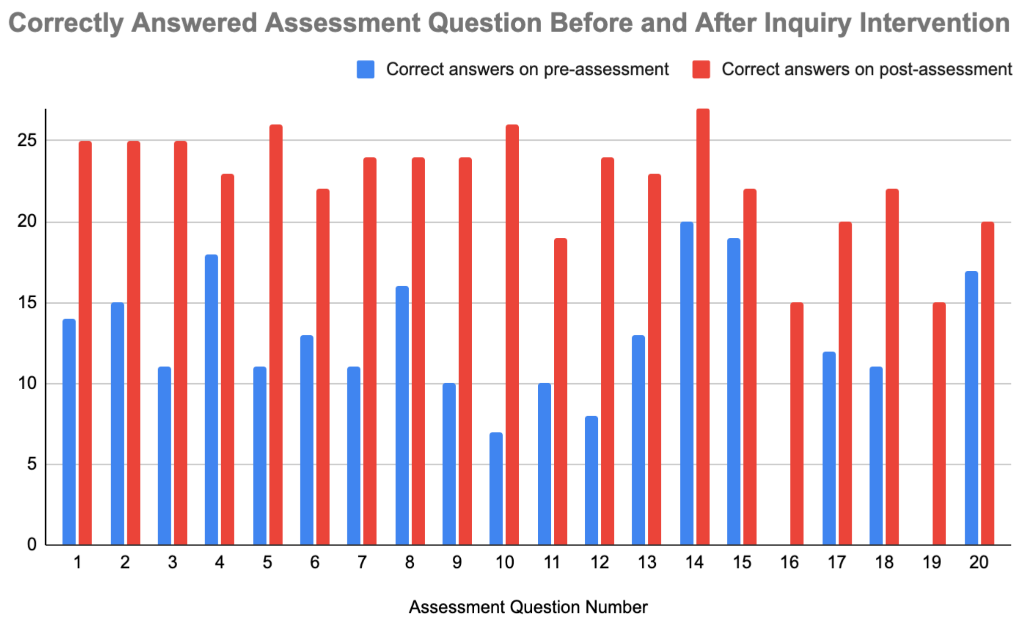
The purpose of this research is to determine to what extent facilitating a weekly inquiry-based investigation for four weeks will improve student scientific inquiry skills and content knowledge in a secondary science evolution unit. It provided data on the relative effectiveness of each of the three different approaches to inquiry-based learning.

Student Understanding of Evolutionary Concepts

The data in this section is meant to represent how the inquiry-based unit affected student understanding of evolutionary concepts and overall inquiry skills in general. In Figure 1, content knowledge was measured using an identical pre-and post-unit assessment that directly addressed 20 common misconceptions about evolution. The average student score in the section being observed on day one of the unit was 44%, and post-unit, that score increased to 83%.

Figure 1

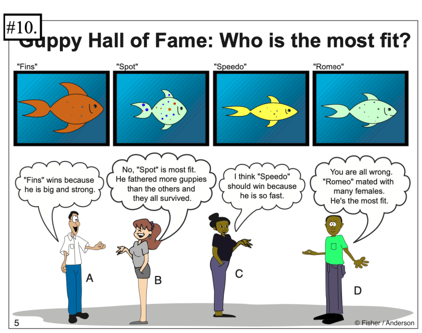
Comparison of Pre- and Post-Unit Assessment by Question



Of the 25 questions on the assessment given, 100% showed improvement between pre- and post-inquiry unit scores. The question that showed the highest student-improvement rate of 70.3% is included as Figure 2. Three other questions showed improvement rates of over 50% each, and these questions are included in Appendix A. These questions are included in this report to give the reader an understanding of the level and formatting of the questions used in this study.

Figure 2

Example of a question from pre- and post-assessment given to students



Finally, while it also had a 56.2% improvement, Question 16 was ultimately dropped due to student confusion. The confusion stemmed from there being multiple correct answers but no indication that students should ‘select all that apply’.

Student Feedback from Student Inquiry Participant Data Form

Figures 3 through 6 reflect the data collected through the Student Inquiry Participant Data form filled out anonymously and voluntarily by participating students. In Figure 3, data from student ranking questions is quantified to show preference. Lower scores show higher ranking: In the survey, students were asked to rank the activities from most enjoyable (1) to least enjoyable (5), then from most educational (1) to least educational (5) based on their learning experiences. Therefore, the Sapiens comic book reading was the most enjoyable activity. In contrast, the least enjoyable was a tie between team activity on caffeine and the online lab. There was a three-way tie between the two teacher-guided activities and the team activity for most educational value. Students assigned the least educational value to the Sapiens reading.

Figure 3

Student Engagement with Inquiry

	Average Rating based on student enjoyment	*Average Rating based on student-perceived educational value*
Team Activity on Caffeine in Plants	*3.21*	*3.21*
Teacher-guided "Is Sammy Alive" Activity	*3*	*3.21*
NOVA Digital Evolution Lab	*3.21*	*3.42*
Sapiens comic book reading	*2.84*	*3.63*
Teacher-guided "Survival of the Sneakiest" Activity	*3.16*	*3.21*

The quotes collected on the Google form from 19 students (of the total 27 participants) suggest an overall positive outlook on inquiry, for example, “The activities are much more helpful in learning than just taking notes”. Additional participation quotes can be found in Appendix B. The common theme was that overall understanding was increased because of one or more of the lesson components aligned with scientific inquiry. As with any lesson, however, there were some students who reported that after experiencing inquiry-based activities, they still preferred the teacher-led lecture-style format of learning.

The following set of charts reflects further student data gleaned from the feedback tool. The first two pie charts (see Figures 4 and 5) show that students did not dislike working with the groups they were assigned for this unit or the pace at which their group accomplished tasks in class. Not a single reporting student disagreed with the statement “I feel that my group works well together during team activities”, and well over 90% of students reported completing all group work within the class time allotted.

Figure 6 provides a visual for overall student approval of in-class inquiry activities. 57.9% of the reporting students expressed a want to participate in inquiry-style learning in future units. 10.5% did not wish to repeat this style of learning, and no students strongly disagreed with the format of the unit.

Figure 4

Student feelings on group work and inquiry

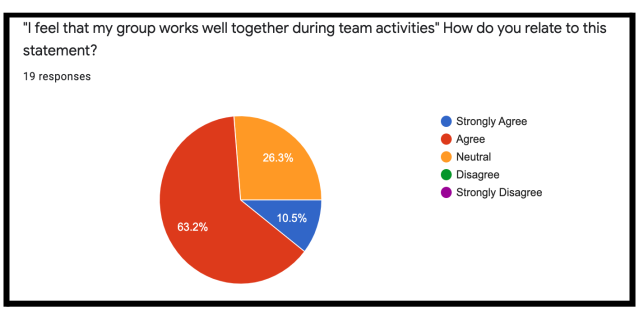


Figure 5

Student Completion of activity in given time

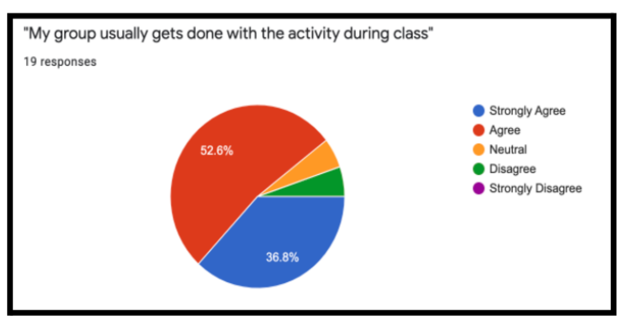
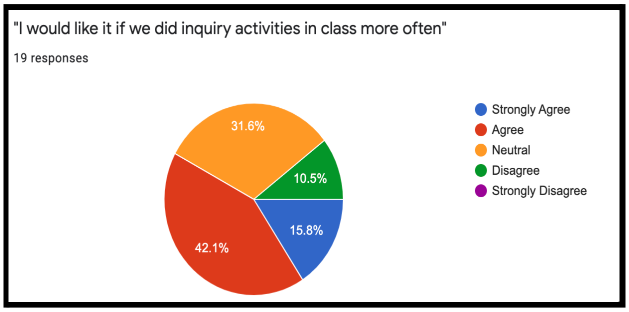


Figure 6

Student motivation to continue with inquiry in the classroom

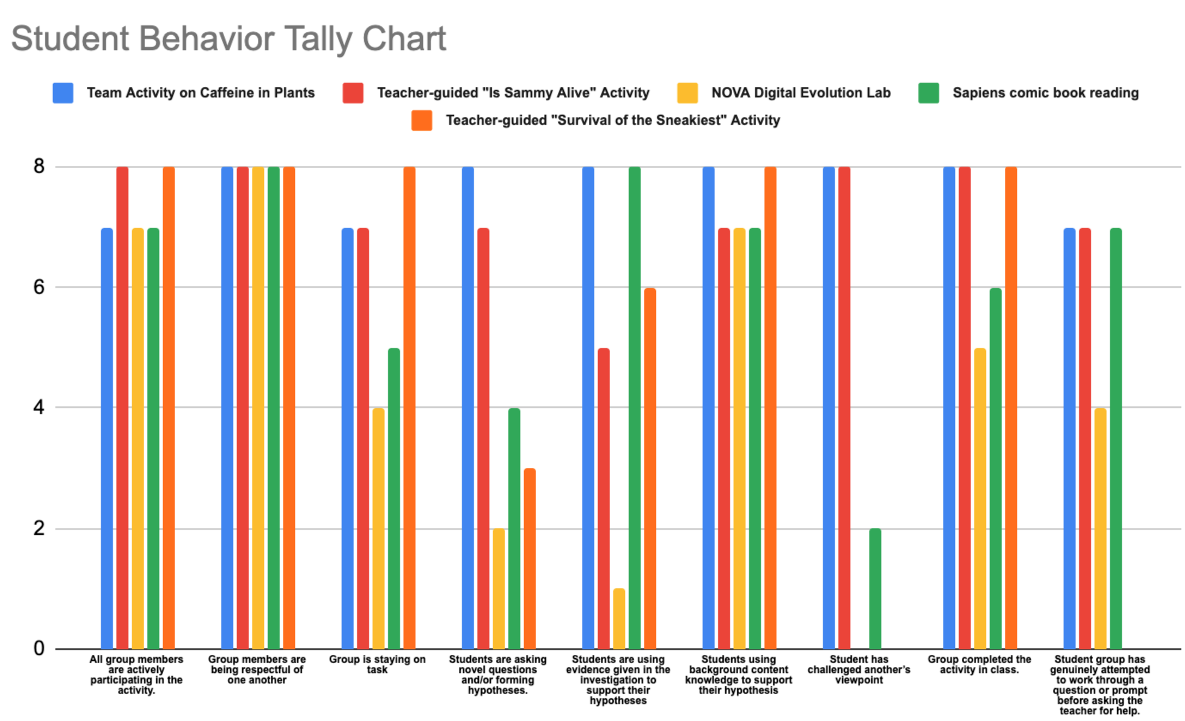


Teacher Perceptions

During the five inquiry-based activities, the teacher kept a tally chart which allowed them to track the frequency of nine specific behaviors that indicate the building of scientific inquiry. The nine behaviors being tracked by the teacher can be seen on the x-axis of Figure 7. The team activity discussing caffeine production in plants was consistently high in all positive student behaviors. The lowest overall was the NOVA Digital Evolution lab. It is worth noting the two teacher-guided activities did not call for as much group work as the other three.

Figure 7

Behaviors observed by the teacher during inquiry-based activities



The teacher journal reflected many of the themes cited in the literature review as common barriers to inquiry learning, including limited class time, limited funds for activities, and less administrative support than expected (outdoor inquiry was not permitted at the time of data collection). The teacher found the student audio recordings of group discussions extremely helpful, but noted that the time spent analyzing lessons was exceptionally time-consuming. Finally, the teacher acknowledged that school COVID restrictions may impact student group work during class. The teacher noticed growth in their students' investigative skills and ability to construct explanations using evidence. Overall, the teacher enjoyed using scientific inquiry in this unit and plans on incorporating it into future units.

Action Plan

After analyzing the data produced by this study, it is clear that students both enjoyed and benefited educationally from the scientific inquiry activities used to teach the evolution unit. Below are the conclusions drawn based on the data collected, the future areas of interest regarding inquiry-based learning in science classrooms, and the limitations of the data collection presented.

Conclusions

Based on the findings of this study, the following conclusions were drawn:

- Curricula that emphasize inquiry-based learning methods are highly effective at addressing student misconceptions.
- Of the four different types of inquiry tested on students (teacher-guided, team activity, individual inquiry, and digital lab), data suggests that students felt that the most educational activities were team activities and teacher-guided inquiry.

- Teacher observation data suggests that the team activity was most effective at promoting inquiry skills, while the digital NOVA lab was least engaging for inquiry purposes.

Courses of Action

- Incorporate more scientific inquiry activities, specifically team activities.
- Experiment with different options for digital activities and/or labs to see what qualities in an online inquiry resource are most valuable.

Study Limitations

Teaching and collecting data during the COVID-19 pandemic made classroom activities quite difficult. Students were wearing masks and were seated three feet apart at all times, and several students were absent for a majority of lessons in the unit due to health concerns. These variables certainly affected overall student understanding, and it is difficult to say exactly what those effects were and to what extent they hindered the effectiveness of any individual lesson.
Finally, I did not have data collected from the previous year of teaching this unit, in which scientific inquiry was not my main goal when presenting content. This study is intended to be a starting point for future research on scientific inquiry in the classroom.

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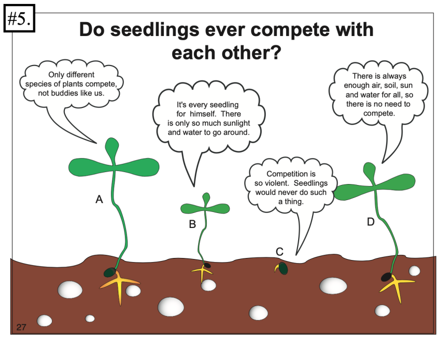
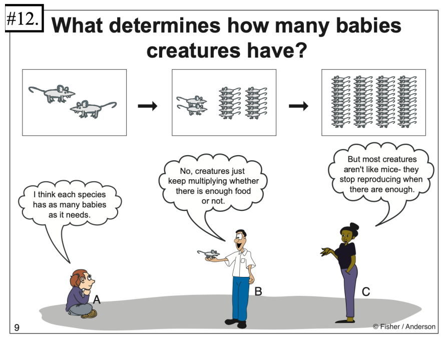
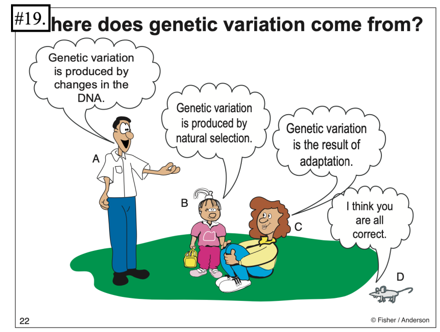
Appendix A
Images from Pre- and Post-Assessment







#5 (Improvement of 56.2%)

#12 (Improvement of 59.2)

#19 (Improvement of 56.2%)

Appendix B
Quotes from the Student Feedback Form

"The activities are much more helpful in learning than just taking notes"

"The hands-on and interactive lessons were so much more effective than just being lectured to."

"I work best in groups because if I'm talking about a question I can come up with Just cause I'm saying to aloud."

"With more fun activities like survival of the sneakiest I feel like I was able to remember the content better because it was simple to first understand and from there I could get a better understanding "

"Group activities help me understand certain topics better"

However, some students preferred an individual activity over group work, and still others found that they still preferred a lecture to group inquiry.

"Individual stuff in class helps me. I like working by myself and figuring things out on my own."

"I work well with a short a focused lecture with short questions to improve my memory of the topic."