

EFFECTS OF INQUIRY INSTRUCTION ON BIOLOGY STUDENTS' ATTITUDES
AND CRITICAL THINKING

by

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Suzanne Martell Wilson

July 2013

DEDICATION

This paper is dedicated to my mother and to the memory of my father, grandparents and great grandfather. These are the people who shaped me and misshaped me so that I find myself in the sixtieth year of my life still in school. I love and loved them all deeply and am happy to have traveled this far on the journey because of and in spite of all that they gave me. I also dedicate this paper to my sister and spring break buddy, Joanne. Finally, I dedicate this paper to my life partner, Jeff and our shared children, Angus, Ellie, Rose, and Wally.

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ABSTRACT

This study measured the effect of student-designed inquiry on students' attitudes and their critical thinking skills. Surveys pre- and post-treatment were used to determine student attitudes. Students' inquiry reports were used to evaluate their written conclusions for a claim statement, data used as evidence and a logical connection to science models. Students made improvements in designing and interpreting their research and increased their positive attitudes toward learning science.

INTRODUCTION AND BACKGROUND

For the past ten years I have taught science at Centralia High School in Centralia, Washington. My teaching assignment consisted of two sections of sophomore honors biology, two sections of general biology and a marine biology class. Prior to teaching, I was a wildlife biologist for more than ten years with the United States Department of Agriculture (USDA), Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory. I conducted studies and published on ecosystem processes related to mammals' response to forest management.

The curriculum that I assembled and used in my biology courses is based on Washington State's Science Learning Standards (Office of Superintendent of Public Instruction [OSPI], 2010). The standards call for students to use and understand scientific inquiry. Specifically, students were expected to report, analyze and communicate scientific results as well as design and critique experimental set ups. I hoped that my action research-based classroom project would help my students to better meet the achievement benchmarks determined by Washington State.

I involved two honors biology classes in my project. Most of these students were taking more than one honors class concurrently and tended to achieve higher grade-point averages than the rest of their grade-level cohort. These students were highly involved in school activities including sports, student government and music. Others were involved outside of school in dance, boxing and church youth groups.

At the time of this study, Centralia was a small town of about 20,000 with an unemployment rate over 12%. More than 50% of the 900 students at Centralia High School received free and reduced lunch. Most students were Caucasian. About 16%

spoke Spanish as their first language. Centralia's main industry, a coal powered electric plant, was the largest single-point producer of greenhouse gases in Washington State. Legislation was passed that will halt the use of coal at the plant in the next decade. This added additional uncertainty to the employment picture for Centralia.

The term inquiry is correctly applied to a spectrum of different types of scientific investigations ranging from descriptions, to comparisons, to correlational studies, to controlled experiments (Windschitl, Kohler, Dvornich, McAllister & Tudor, 2004). In this project, I chose to focus my research primarily on increasing students' abilities to design, complete and communicate about *controlled experiments* because this type of inquiry is emphasized on high stakes tests. My research focus was prompted by my observation that many of my honors biology students did not grasp the essential inquiry process that is at the heart of science. Most were able to parrot the steps and jargon of an experimental investigation, taught as the *scientific method*. But rarely had they experienced the problem solving that accompanies each step of authentic inquiry. For the most part, my students had little or no practice developing methods and carrying out investigations of their own design, not even with questions supplied by the teacher and even more rarely with student-generated questions. Generally, I encountered students who had learned scientific process by carrying out cookbook procedures intended to answer teacher-provided questions. Students believed that teacher-specified procedures and methods of data analysis should lead to predictable results and foregone conclusions. Students expected their inferences to be uniform and consistent with what other students found. When students' results differed from their peers, they would rush to correct their 'mistake' rather than to *think* about factors that might explain variation in the data. I also

noticed that very few students' written conclusions about their investigations included any references to scientific models or theory.

While my action research-based project delved into student-centered inquiry, specifically student-designed *controlled experiments*, I also continued to provide students with some scripted inquiry activities. Scripted inquiry in my classroom helped to cover required content in a timely manner. Scripted inquiries tended to be descriptive or comparative in nature. I chose them when I wanted students to observe or investigate phenomena relevant to specific content objectives such as the cellular nature of life or the structure of DNA. Secondly, I wished to give students experiences that mimicked the procedures and group cooperation used in various scientific fields. I thought these experiences would scaffold students' abilities to design and carry out their student-designed controlled experiments by giving them practice with experimental models. However, I noticed that when students performed completely scripted investigations they did not pay attention to relationships among variables, and procedures were often black boxes with students not thinking about the purpose of their actions. There was no struggle about *how* to answer a question when the procedures had been laid out for them and that certainly was misleading from the perspective of understanding how scientific knowledge is created. Thus, I hypothesized it would be a more realistic experience and more cognitively demanding for students to design inquiries, specifically controlled experiments, of their own. I thought student-designed controlled experiments would be more intrinsically revealing as to how science operates as a series of small incremental steps—including blunders—that lead to new insights. Students would have to make

decisions about variables and thus come to discriminate among properties such as cause and effect, correlation, random events and extraneous factors.

Since my students and I had little experience with student-designed controlled experiments, it seemed prudent to gradually move from wholly teacher-designed and directed investigations first to a hybrid version where the teacher provided a general problem and students defined their own particular question nested within the general problem. For instance, when I prepared students to embark on their self-designed controlled experiments, I would pose general questions such as what are some abiotic factors that might influence how brine shrimp select a particular habitat? And, what factors might control the rate of enzyme action or the rate of photosynthesis? I became more of a coach and collaborator. I helped students each step of the way as they clarified a specific answerable question, made a prediction, designed protocols, selected equipment, ran pilot studies, gathered, analyzed and presented data as evidence for their claims and theory-based conclusions. Students would use me as a sounding board for their ideas and I would ask them to explain the rationale for their procedural choices, inferences and scientific arguments.

My primary focus question for this study was, Can inquiry supported with appropriate scaffolding for writing and analysis help students to communicate their findings logically by making connections between their claims, evidence, and scientific theory? The sub-question was, Does the use of student-designed inquiry impact student attitudes toward science and improve students' science skills?

CONCEPTUAL FRAMEWORK

Inquiry is defined as students designing, conducting and analyzing their own research (National Board for Professional Teaching Standards [NBPTS], 2003). To grasp the use of inquiry in real-world science, students must understand how predictions, based on existing theory, and empirical data, evaluated statistically, are used to form logical arguments supporting inferences (American Association for the Advancement of Science [AAAS], 1993; Ruiz-Primo, Li, Tsai, & Schneider, 2010; Sampson & Schleigh, 2013). Student understanding of the nature and application of inquiry in the field of science is not adequately supported by traditional classroom laboratory experiences where the investigative question, methods and sometimes the outcome are predetermined. In order for students to understand and experience the creativity and versatility of inquiry, as well as the logical and empirical characteristics, they must embark on self-designed investigations and be given adequate scaffolding and time to pursue the endeavor (AAAS, 1993; Llewellyn, 2005).

In an effective inquiry-based classroom, the teacher is an active learning participant who knows students' science backgrounds, develops content frameworks and sets goals for student learning and assessment (NBPTS, 2003; National Research Council [NRC], 1996). Teachers should present science content using varied strategies and mediums. Students should learn how the underlying scientific theory was developed and verified through the inquiry process (Educational Broadcasting Corporation [EBC], 2004). During student-centered inquiry, the teacher is not a bystander, but an active mentor who engages students through questioning as they plan, execute, analyze and disseminate the findings of their own inquiry investigations (NRC, 1996; NBPTS, 2003).

The teacher challenges and supports students and models the curiosity, excitement and skepticism that characterizes the practice of science (Llewellyn, 2005; NRC, 1996). The intent of an inquiry-rich classroom is for students to understand and experience how scientific knowledge is actually created (NRC, 1996; EBC, 2004).

Classroom inquiry is based not only on the idea that students can learn and appreciate science more fully by employing methods and analytical approaches used by scientists (NBPTS, 2003), it also has roots in the constructivist school of education theory (Llewellyn, 2005). According to constructivist education theory, students learn by exploring objects and phenomena in their environment and by forming subjective explanations (EBC, 2004). However, inquiry-based science instruction does not automatically translate into increased student achievement on tests. Hung (2010) used structured equation modeling on data from over 9,000 students on the Trend in International Mathematics and Science Study 2003 (Martin, Mullis & Chrostowski, 2004). He found that inquiry-based science instruction had only a small direct impact on achievement and that positive student attitudes toward science raised achievement more. Hung (2010) suggested the positive impact of inquiry strategies on student attitude could indirectly affect achievement. However, the aspect of inquiry responsible for changed student attitudes was not derived from his analysis and he suggested further investigation was needed. Hung (2010) suggested that instruction based in inquiry that strengthens students' positive attitudes toward science by making it relevant, interesting and doable, could cultivate student interest in science and this might improve achievement. Students' attitudes and especially their motivational beliefs are thought to have an impact on

student achievement in general (Elliott & Church, 1997; Beghetto, 2004; Russell & Hollander, 1975).

In a smaller study, the use of inquiry-based learning supplemented with videoconferencing that connected students to scientists/mathematicians produced a significant gain in achievement and in positive student-attitudes toward science and toward their own abilities. Natural resource scientists taught students about biodiversity, ecology and mapping bear populations. Following the inquiry-based project, there were significant gains in achievement for both rural and urban students on teacher-designed tests. Qualitative analysis of student interviews revealed deeper understanding of topics and higher interest in science and math with students reporting these gains persisting, in some cases, for at least two years. However some students desired more interaction with their teacher and other students became bored with the length of time spent on inquiry. The novelty of videoconferencing initially inspired students; but over time, videoconferences had to be adapted to be more student-centered and less centered on the mentors to maintain student interest. Students did not like to present their work during videoconferences unless their teacher had checked it. Mentors had the potential for negative impacts on students' learning and attitudes if mentors did not treat students appropriately (Li, Dyjur, Nicholson & Moorman, 2009).

Multiple middle school classrooms were studied to see how often students wrote analysis following inquiry-based investigations, what the characteristics and quality of those explanations were, and the correspondence between the quality of explanation and student achievement. There was a positive correlation between student learning and the quality of students' interpretation and analysis of inquiry activities in students'

notebooks. Notebook entries were evaluated on how well students supported their claims about their hypotheses with evidence and reasoning. However, only 18% of student notebooks showed complete written analysis and reasoning subsequent to inquiry activities. Most students only provided a claim without evidence from their data or logical arguments to support their claim. Although writing evidence-based explanations is key to student understanding and conceptual change, in many classrooms this was lacking from over 40% of students' science notebook entries. Classrooms serving the most disadvantaged students were the least likely to have students go beyond the claim stage of a scientific analysis. In one classroom the data were the endpoint of the inquiry process with no further writing on the part of students. Scaffolding that prompted students to provide specific types of information for a relevant explanation was superior for teaching and scoring. Prompts that provided students with a section heading alone did not give students enough guidance to develop the chain of evidence and that would allow them to construct a notebook entry that was structured with a claim, evidence and arguments (Ruiz-Primo et al., 2010).

Some science teachers may not be adequately prepared to lead students in conducting inquiry, analyzing results and reporting their findings. A study of pre-service teachers found misconceptions concerning authentic inquiry were pervasive, and these misconceptions were frequently supported by textbooks, the media and even by science educators, cumulatively leading to a folk theory of inquiry (Windschitl, 2004). Essential features of authentic inquiry such as developing and modifying research questions, appreciating logistical constraints and equally valuing positive and negative outcomes in relationship to the hypothesis appeared to be consistently understood among the pre-

service teachers. However, the pre-service teachers often held a belief in a “scientific method,” and failed to employ statistical analysis. Other problems that pre-service teachers had was stating hypotheses as guesses and disconnecting the inquiry process from relevant theory or models. Pre-service teachers did not provide arguments for their claims, evidence-based explanations from their data nor did they make links that reflect the relationship of their inquiries to scientific models or theory. Teachers with science-research backgrounds or greater preparation in science content were more likely to use inquiry-based strategies during their apprenticeships (Windschitl, 2004).

Science teacher education programs should instill the knowledge and skill associated with model- or theory-based inquiry. Pivotal content area ideas would be defined as models. These key ideas would form the basis for inquiry investigations and the argumentation that weaves together the data and interpretation. A folk theory of the scientific method endures because it is formulaic and can be conveyed with authoritative words: *question, background, hypothesize, gather data, and form conclusions*. Recommendations for an authentic-inquiry curriculum may be ineffective at dislodging folkloric science teaching (Windschitl, 2004). For example, no mention of data interpretation strategies and constraints was given in a description of teacher workshops on science notebooks and inquiry (Mintz & Calhoun, 2004). Focus group interviews of science-education students at Swedish universities found a conflation of the term *experiment* with *laboratory task*. The pre-service science educators failed to make an explicit distinction between inquiry and a classroom activity (Gyllenpalm & Wickman, 2011).

Teachers may not be adequately trained in data interpretation and explanation and might be unprepared to teach this critical piece of the inquiry-learning process. In particular, teachers may not be able to reconcile the random variation found in data based on observations with their beliefs that natural phenomena are described by mathematics (Bowen & Roth, 1999). This is potentially a significant loss of opportunity for student learning given the high positive correlation between quality of student explanations and student achievement (Ruiz-Primo et al., 2010).

METHODOLOGY

My action research-based classroom project was conducted over an eight-month period from September 2012 to May 2013. This time period spanned seven biology units that included the nature of science, biochemistry, cellular structure and function, the environment of the cell, photosynthesis and respiration, genetics and population ecology. Data used for this study were gathered during three units containing an inquiry piece that was a student-designed controlled experiment where students analyzed data and formed conclusions based on their own experimental outcomes. The units were the nature of science, biochemistry and photosynthesis. Research participants were 44 high school sophomores from two honors biology classes. Data from the two classes were combined for analyses. The research methodology for this project received an exemption by Montana State University's Institutional Review Board and compliance for working with human subjects was maintained.

In the first unit, the nature of science, students designed and conducted a controlled experiment testing the influence of pH on seed germination. To prepare

students for this inquiry, I had them do a simple activity exploring the pH values of common substances. Through lab observations, textbook readings, video and classroom discussions, students learned about the chemistry of acids and bases and the effects of acid rain. Students worked individually to develop research questions they could pose regarding pH and seed germination. Students then convened in their assigned four-student teams to come to consensus on the direction of their team's inquiry. Each team had two weeks in which to design and conduct a controlled investigation, analyze results and create a report. Groups made all their own decisions about study design, analysis, and inferences drawn from their controlled experiment. I served as a resource by asking questions about the rationale behind groups' decisions. I did not mandate how groups were to present their data or construct their conclusions in order to determine baseline skill-levels. Group members each wrote part of their group's inquiry report, which was presented during two poster sessions. Half of each group presented their poster to small groups of peers during the first session and then switched with the other members of their group for the second session. I took notes in my teacher journal on student posters and on student discussions about their research. My journal observations qualitatively characterized the baseline abilities of the class as a whole in developing research questions, gathering background information, testing hypotheses and obtaining reliable data and forming conclusions. I collected all posters for quantitative assessment. The assessment was not shared with students. Students did not revise nor revisit their team's poster after their poster session.

To assess the pH and seed germination posters and reports on three subsequent inquiries, catalase experiment, timed-test scenario and the photosynthesis experiment (all

described below), I used the CLER scoring rubric (Appendix A). I ranked performance on five rubric elements, data table, graph, conclusive statement, use of evidence, and connection to science theory as *excellent*, *good*, *deficient* or *missing* and supported my appraisal for each element by using a checklist embedded in the rubric. The checklist allowed me to point out what students had done well and what was weak or missing from their data, analysis and conclusions. I also wrote clarifying notes to students on their CLER rubric and directly on their reports. Students were encouraged to continue refining their reports especially the data table, graphs and conclusions in their reports after being given their CLER evaluation.

For analysis purposes, CLER results were compared among the three individual reports for each of the five rubric elements, data table, graph, conclusive statement, use of evidence and connection to science theory. I compared the percentage of students falling into each proficiency category, *excellent*, *good*, *deficient* or *missing*, and constructed bar graphs in Excel to display the results. I visually inspected the graphs to determine if there were distinct changes or trends in students' proficiency during my action research.

In the second unit, biochemistry, students first conducted a pre-designed controlled experiment testing the effects of catalase concentration on hydrogen peroxide decomposition. This activity allowed students to become proficient with laboratory techniques they could then apply in a student-designed inquiry to investigate the effect of temperature on the catalase-hydrogen peroxide reaction. In groups of four, students designed, tested and conducted their own controlled experiment to explore this relationship. Each student kept track of their group's research question, hypothesis, methods, observations and quantitative data in their individual science notebook. At the

end of the temperature-catalase inquiry, each student was required to submit a typed report for which the data analysis and conclusions were exclusively their own work. Reports were expected to have a data table created in Word and a graph in Excel. The conclusions section of the report was expected to have a claim statement, evidence from the data and reasoning linked to science models. I evaluated each student's report using the CLER rubric (Appendix A) as described above.

At the end of the biochemistry unit students were given a timed test consisting of a scenario describing a controlled experiment using the catalase enzyme at different pH levels. Students were asked to organize and analyze the data and write their conclusions using a laptop computer. They were to create a table in Word, graph in Excel and write a conclusion for the scenario that had a claim statement bolstered with evidence from the data and reasoning linked to science models. I used the CLER scoring rubric as described above (Appendix A) to assess students' presentation of data and handling of conclusions.

In the third unit, photosynthesis and respiration, individual students were asked to list several physical or chemical factors that might affect the rate of photosynthesis and then to rank their ideas as the most, somewhat or least desirable question they would like to research. I then compiled students' choices and assigned students to groups and research topic based on their interests. Not all students got their first choice topic but none got their last choice. I introduced students to materials and methods that they could use to assay the rate of photosynthesis. Student groups then designed controlled experiments testing the effects of one of the following physical factors, pH, color of light, intensity of light, temperature, and natural vs. fluorescent light on the rate of photosynthesis. Students worked together in groups of four refining their research

question, hypothesis and predictions. They developed methods, conducted pilot studies and finally, refined their protocols and gathered data. Students recorded notes on their research in personal science notebooks. I interacted with each group on a daily basis and formatively reviewed their individual and group progress. I encouraged students to generate ideas, brainstorm and test solutions to their problems. Students were authorized to test and refine their procedures through pilot studies and to improve their protocols throughout the inquiry. After groups completed the data collection phase, each student worked independently to complete a report with particular attention to the results, analysis and conclusions sections. I used the CLER scoring rubric (Appendix A) to assess students' reports as described above.

I used the Intervention Survey (Appendix B) to find out if student-designed inquiry with scaffolding for writing analysis and conclusions had an impact on student attitudes. I gave the survey once as a baseline before students designed and carried out any controlled experiments and once following the final student-designed inquiry. On the Intervention Survey, students selected answers they felt most represented their attitude from among Likert-style choices of *strongly disagree*, *disagree*, *undecided*, *agree* and *strongly agree*. Students were asked how they felt about working on open-ended investigations, designing their own research and forming sound conclusions using evidence and theories in order to see if their attitudes toward science changed during this project (Russell & Hollander, 1975). Broad questions, not only those germane to science, were also included in the questionnaire in order to investigate any potential changes in students' motivational beliefs (Elliot & Church, 1997; Beghetto, 2004). Questions eliciting student attitudes, pre- and post-treatment toward learning science and

conducting investigations were compared with Fisher's Test (Langley, 1970). Intervention Survey data were tallied for descriptive rankings (e.g. *strongly disagree*, *disagree*, *undecided*, *agree* and *strongly agree*) for the pre- and post-treatment data sets to a numerical matrix. The open-source statistical R package was used to subsequently perform a Fisher's Test on the transformed data. Statistically significant differences between pre- and post-treatment results were recognized at the $p \leq 0.05$, significance level.

The Intervention Survey had three open-ended questions allowing students to give information they deemed relevant. These data were not quantified and were treated as qualitative observations and are discussed separately.

A second set of early-treatment and post-treatment data came from the Skills Self Confidence Survey (Appendix C). Students ranked their confidence in recognizing and designating the contours of a controlled experiment and in interpreting and evaluating experimental outcomes as *none*, *low*, *medium*, and *high*. This survey was specifically targeted to student recognition of and confidence in using the Washington State Standards' vocabulary for experiments and scientific communication. The Skills Self Confidence Survey was given first, four weeks after students completed their pH and seed germination inquiry and second, following the completion of their photosynthesis inquiry. The data were summarized and compared between the pre-treatment and post-treatment responses using a Fisher's Test. The Skills Self Confidence Survey data were transformed from descriptive rankings e.g. *none*, *low* etc. to a numerical matrix. The open-source statistical R package was used to subsequently perform a Fisher's Test on the transformed data. Statistically significant differences between pre- and post-treatment

results were recognized at the $p \leq 0.05$, significance level.

My final source of data was qualitative. I used report excerpts as examples of writing that met or did not meet the goals of my action research. All data collection instruments are displayed in Table 1.

Table 1
Triangulation Matrix

Focus Questions	Data Source 1	Data Source 2	Data Source 3
<i>Primary Question:</i> 1. Can student-designed inquiry supported with appropriate scaffolding for writing and data analysis lead students to communicate their science findings logically by making connections between their claims, evidence, and scientific theory?	CLER Analysis	Student inquiry reports	Teacher Journal
<i>Secondary Questions:</i> 2. Does the use of inquiry and authentic data analysis impact student attitudes toward science?	Pre and post-Intervention Surveys	Student inquiry reports	Teacher Journal
3. Does the use of inquiry, including authentic data analysis impact student confidence in their science skills?	Skills Self Confidence Survey	Student inquiry reports	Teacher Journal

DATA AND ANALYSIS

In the first instructional unit, 11 teams designed and completed an experiment testing the effect of pH on seeds. I challenged teams to explain their research plans by asking them how they were going to answer their research question with the equipment they had available. I pushed students to carefully consider their equipment choices and

procedural protocols but ultimately left the decisions to them. One student said, “We’ll have the same amount of everything else like heat and the amount of light and like all the same except for the pH.” I asked his team what type of variables those would be. The students then discussed controlled variables as contrasted with a control condition. Ultimately, all teams isolated their manipulated and controlled variables and established a control condition.

Once teams had decided on equipment, materials and methods to germinate and observe seeds sprouting under their specified experimental and control conditions, I expressed my concern to students that their responding variables were not clearly defined. One student said, “We have to find what to look for.” I encouraged students to be specific about which data they were actually going to collect. All teams had some trouble with defining their responding variable(s). Students had vague descriptions like, “Whichever ones grow fastest.” Some teams determined specific responding variables such as number of days for seeds to germinate or average length of seedlings. But even those teams failed in planning how to capture data from their replicates (the individual seeds). I urged students to strategize how they were going to get and record their data. I noted in my Teacher Journal that my students were slow to move forward to determine exactly what their responding variables could be and while they knew they needed multiple trials, they did not have a clear plan for collecting data from their replicates.

Over the early days that students were collecting data, I prompted them to make a plan for how to display and analyze their results even though they did not have much data. A girl said, “We have pH data and we know how many days we have to get data.” Another student said, “We got the number of seeds for each pH.” Groups brainstormed

potential comparisons among treatments. I did not tell students how to present their results or what graphs and tables they might include. I only told them that everything on their posters, except pictures, had to be typed.

As the student-designed inquiry progressed, teams solved or failed to solve their problems and setbacks. For example, one team wetted their seeds with a meager amount of water and did not cover their petri dishes causing excessive drying. The team did not adjust their methods and checked dry petri dishes each day to find that no seeds had germinated. When a different team was analyzing data, they discussed various things that went wrong with their experiment. One student said, “We pretty much all agreed that the first way we did it is was just not accurate at all and was just not going to work.” Another student then said, “So it’s a good thing we redid our experiment.” I asked them if they had captured their unsuccessful first attempt in their report and said those were good observations to include. I let students know that they had done good work because I wanted them to understand that there is a learning curve in developing sampling techniques and that pilot studies are frequently part of scientific investigations.

While examining data, a team asked if they would get a bad grade if they did not find any differences in seed germination between pH levels. I explained that rejecting or accepting a hypothesis was equally valid. These students had the misconception that an investigation had no value if the hypothesis was not supported by the data. The students thought a rejected hypothesis reflected badly on their abilities. I noted in my journal that this perception was extremely misleading about the nature of science and might damage students’ attitudes toward learning science. I noted in my Teacher Journal that it would be good to instruct students to say *the data do not support my hypothesis*, rather than

allowing students to say *my hypothesis was wrong or incorrect*. I made a note to tell students they can use the null hypothesis or the alternative hypothesis for any inquiry.

Eleven posters on the effects of pH on seed germination were produced. Ninety-one percent had a background statement. Forty-five percent of the posters had background research with information on the effects of low pH solutions (acid rain) on plant tissues. Forty-five percent of the posters had general background research on the effect of acid rain but without specific effects on plant tissue being mentioned. None of the background research was about the seed types that were being used in the student-designed inquiries.

For the most part, posters had a hypothesis, materials list and methods written in numbered steps. Some included photos of the experimental set ups. All posters had a computer-generated data table. Tables tended to have descriptive observations and where quantitative data were presented summary statistics such as averages were usually lacking. Only 27% of the posters had a computer-generated graph. All posters had a conclusions section with a claim statement and data used as evidence. Only 18% of posters had a reference to a scientific model or theory in the conclusion section (Table 2).

Table 2
CLER Evaluation of Poster Elements, pH and Seed Germination Inquiry (N = 11)

	Table	Graph	Claim Statement	Evidence	Science Theory
Excellent	2	2	3	2	0
Good	6	0	5	7	1
Deficient	3	1	3	2	1
Missing	0	9	0	0	9
Total	11	11	11	11	11

At the conclusion of the poster symposium, many students indicated to me they had learned a lot and that while it was difficult to make their own research decisions, they had tapped into cooperative skills they rarely used. Students told me that they gained insight from the findings of other teams because while their research questions were similar, none of the teams had exactly the same experimental design or results. Students said they enjoyed the creative work within their teams and the skeptical nature of the symposium as they discussed each other's work. The student-designed inquiry and poster session helped me to get to know my students and they me early in the school year. Because of the coaching stance that I took, students had to ask me questions and answer mine in small group settings. I was able to see which students presented their ideas clearly and which were confused by their own team's work. The data that I derived from the pH effects on seed germination posters was limited because it represented teams rather than individuals.

Over the inquiries that followed, the student-designed catalase experiment, the timed-test scenario and the student-designed photosynthesis experiment, students' scores

on data tables fluctuated. On the catalase report 47% of students' tables were scored *excellent*, 31% *good* and 22% *deficient*. On the timed-test scenario the percentage of students' tables scored as *excellent* declined to 39% but tables scored as good climbed to 49% and tables scored as deficient dropped to 12%. Tables in the photosynthesis reports all were scored excellent or good, 85% and 15% respectively (Figure 1). Not all students used the entire two hours to analyze the scenario and write complete results and conclusions using the CLER rubric. Students did not have time constraints when preparing their catalase and photosynthesis reports and they were able to get help from peers and me.

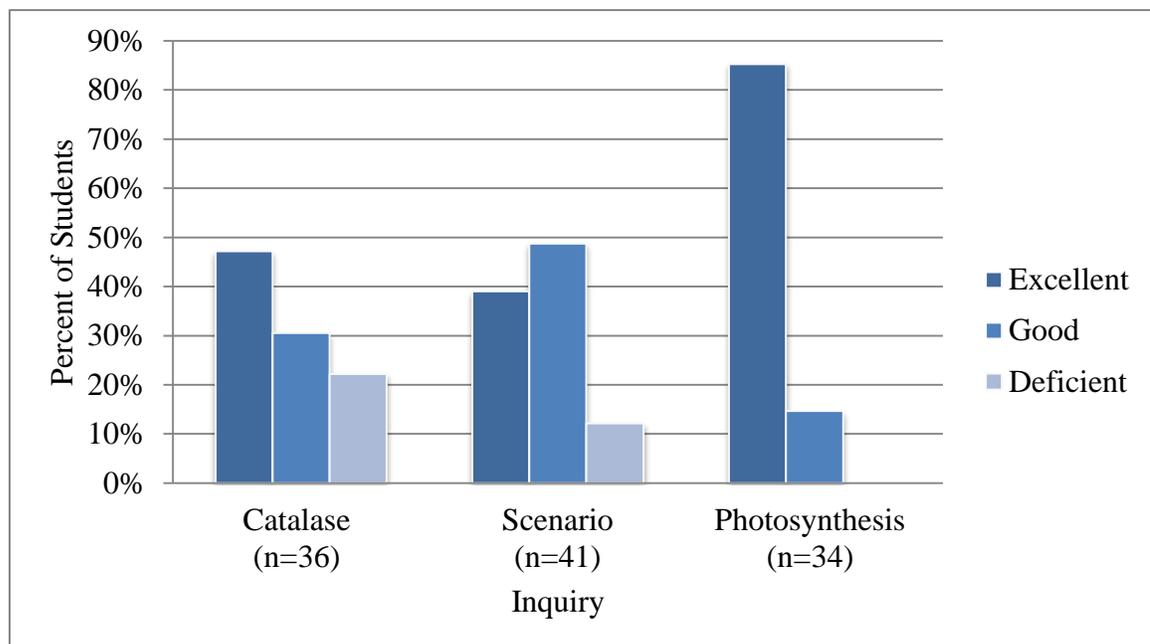


Figure 1. Data table scores for inquiry reports, ($N = 44$).

All students gained experience in creating graphs (charts) in Excel over the course of the project. On the catalase inquiry 6% of reports were turned in without a graph but on the two subsequent reports, scenario and photosynthesis, all students that were required to, produced a graph of their data in Excel. Twelve percent of students were

given a waiver from creating a graph for their photosynthesis report because their experimental results were descriptive, not numeric. The percentage of graphs scored as deficient was similar, 11%, 12% and 9% for the catalase, scenario and photosynthesis reports respectively. Improvement in graphing was observed when graphs ranked as excellent climbed from 44% on the catalase report to 59% on the two subsequent reports. Student graphs scored as good declined across the inquiry series from 39%, to 29% and finally to 21% (Figure 2).

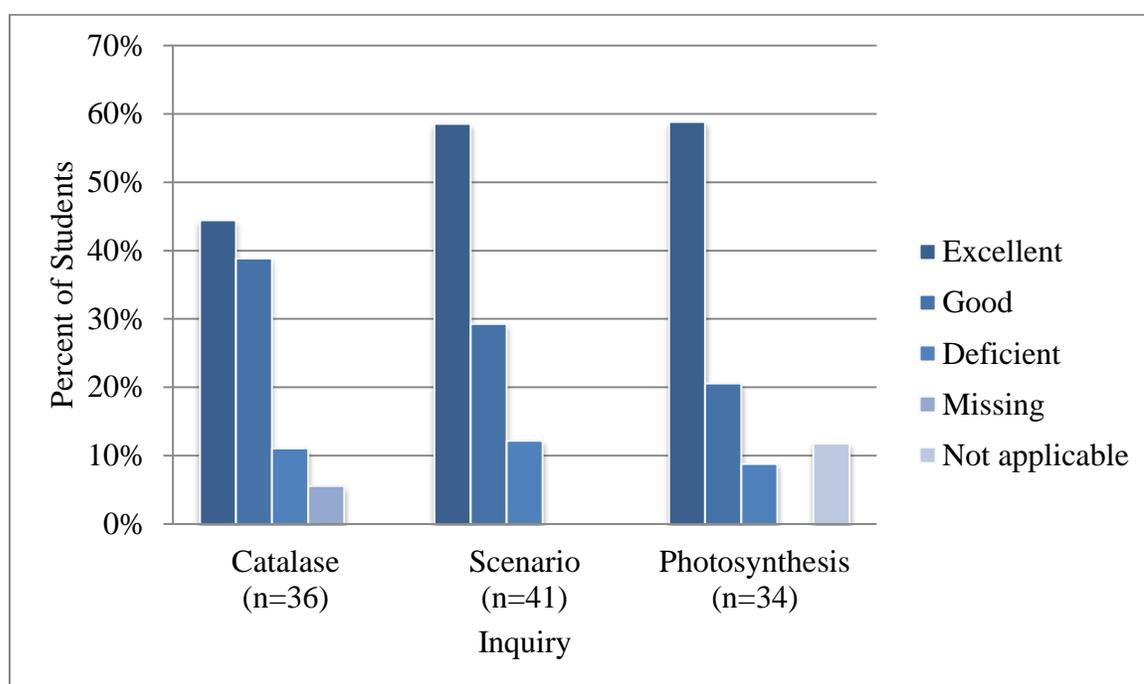


Figure 2. Graphing scores for inquiry reports, ($N = 44$).

Claim statements with scores of excellent climbed from 14% to 39% and ultimately to 76% on the catalase, scenario and photosynthesis reports respectively. One student's claim for the catalase inquiry read, "We are able to conclude from our data that the higher the temperature, the higher the reaction rate." While the statement was clear, it was wildly inaccurate so the claim statement was scored deficient. The same student's claim for the timed-test scenario was, "Our prediction of saying that when the acidity of

potato juice decreases, the volume of foam increases was accepted up until the highest level of pH potato juice had been added with hydrogen peroxide.” The claim did not exactly convey the non-linear relationship between variables, but the student conveyed the general idea and got a score of good. On the photosynthesis report the same student’s claim read, “The hypothesis, if dandelion chads are dropped into water with a higher CO₂ concentration then the rate of photosynthesis will increase until a certain point where it will be constant because the stoma may only take in so much CO₂ at a time, was rejected with our data.” Finally, the student received a score of excellent on the claim statement. The claim was accurate according to his data and was stated unambiguously. As scores of excellent increased, scores of good and deficient declined (Figure 3).

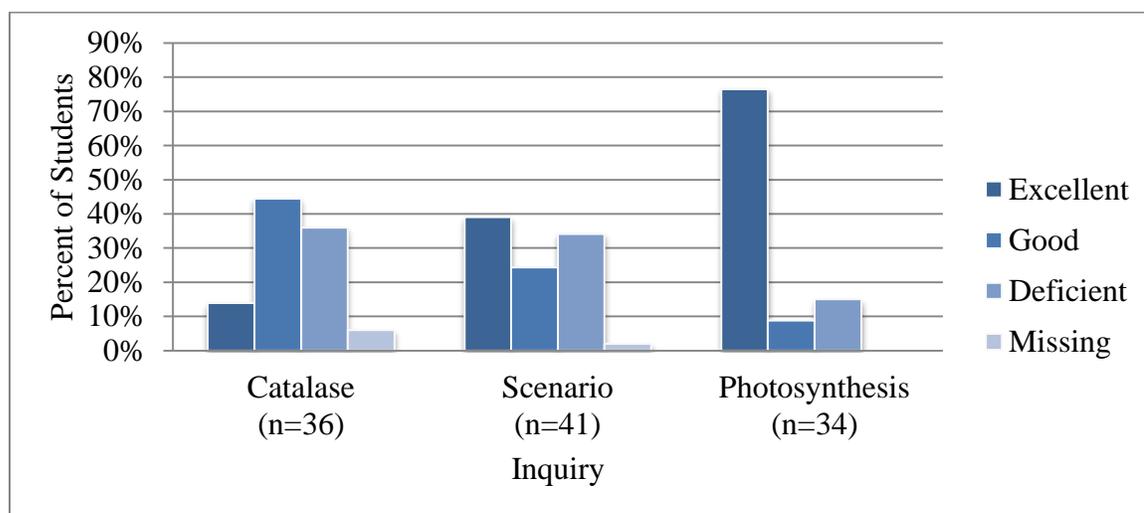


Figure 3. Claim statement scores inquiry reports, ($N = 44$).

Students’ scores trended upward in using data as evidence in their conclusive remarks. In the first inquiry report on catalase less than half the student reports were scored either excellent or good, 14% and 33% respectively. One student used her data extensively in her conclusions but she misconstrued the meaning of the data. “My data showed a ‘U’ shaped line which showed the middle temperatures as having the slowest

reaction rates.” Her middle temperatures in fact had the fastest reaction rates. Her use of the data was graded deficient. On the second inquiry report, scenario, only 5% of students made complete and accurate use of the data however, 78% received a score of good (Figure 4). The same student as above received a score of good on her use of data as evidence in the scenario report. She wrote, “The catalase with the least amount of enzyme (pH 6) in it produced on average 24 mm, while at pH 8 it had 42 mm. However at pH9 it had a drop to 30 mm of foam.” She recognized the trend in the reactions but conflated pH with enzyme concentration. The data depicted the functional pH range for an enzyme and its activity rate along that continuum. Some students only reported the low- and high-end of the pH range where the enzyme was active and, unlike the student above, were not explicit about the optimal pH (highest enzymatic activity). By the third inquiry report in the series, photosynthesis, a trend upward in scores for use of data was evident with 44% scored as excellent and 35% scored as good. This time, the same student as above received a score of excellent for her use of data. An excerpt reads, “Photosynthesis worked fastest in our experiment with the source of light 20 cm away (the highest intensity tested), at an average of 8 minutes and 7 seconds. All five chads came up within the same minute, with the first coming up at 7 minutes and 46 seconds and the fifth coming up at 8 minutes and 37 seconds.” In this excerpt the student gave the average reaction rate and the range of the replicates. All students used their data as evidence in their photosynthesis report (Figure 4).

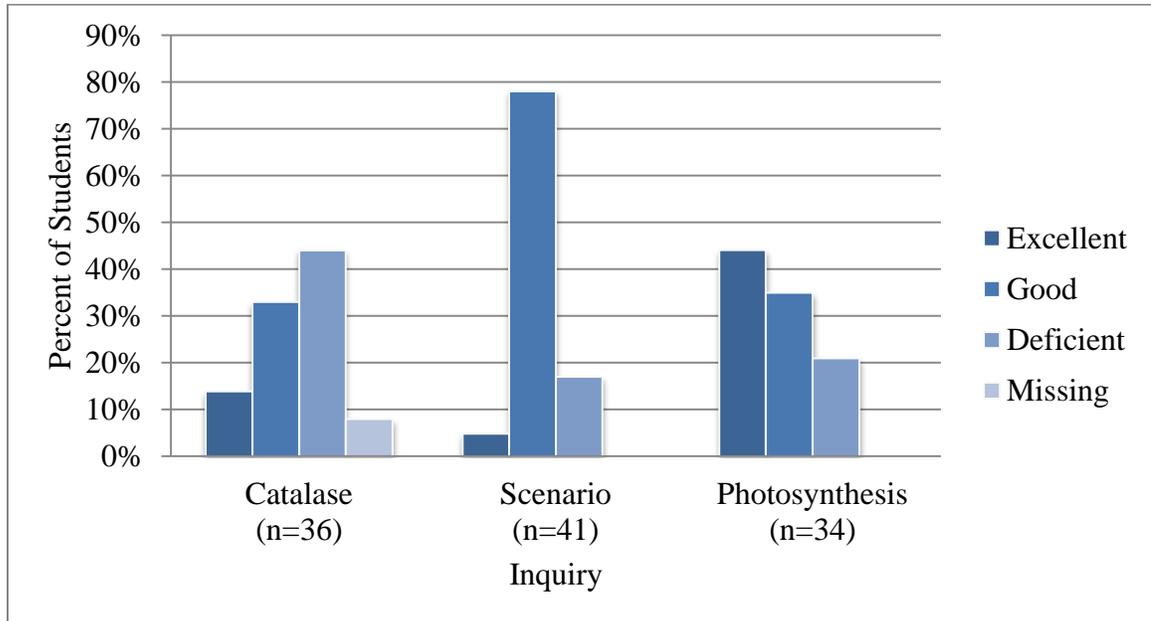


Figure 4. Use of data in conclusions scores for inquiry reports, ($N = 44$).

Scores on incorporation of scientific theory into the conclusions of student reports trended upward across the three inquiries. For example, one student received scores of deficient, good and excellent on the catalase, scenario and photosynthesis reports respectively. In his catalase report he wrote, “The theory of manipulated water temperature on the catalase enzyme ...then the fastest (enzyme) reaction time will come about because of particles gaining kinetic energy.” His statement was scored deficient because his data and enzyme theory directly contradict his statement. The same student received a score of good on the scenario report. He wrote, “The volume of the foam increased due to the catalase enzyme reacting with the best shape to fit into the peroxide substrate, however the pH level increase to 9 and the increased level disfigured the enzyme shape and couldn’t fit into the substrate efficiently.” He was on the right track as far as theory but did not express his ideas clearly. On the photosynthesis report, this student’s use of theory was scored excellent. He wrote, “According to a study from the University of Colorado Boulder, students analyzed the effect of red and blue light on the

rate of photosynthesis (for Juniper needles); they discovered red light conducts faster rates than blue light which is what we found in our experiment.” For all students, reports with a score of excellent for use of theory were 8%, 7% and 44% for the catalase, scenario and photosynthesis reports respectively. The proportion of reports turned in with no apparent attempt to relate the inquiry conclusions to theory were 44%, 54% and 29% for the catalase, scenario and photosynthesis reports respectively. Seventy-one percent of students incorporated scientific theory into their conclusions for the photosynthesis inquiry (Figure 5).

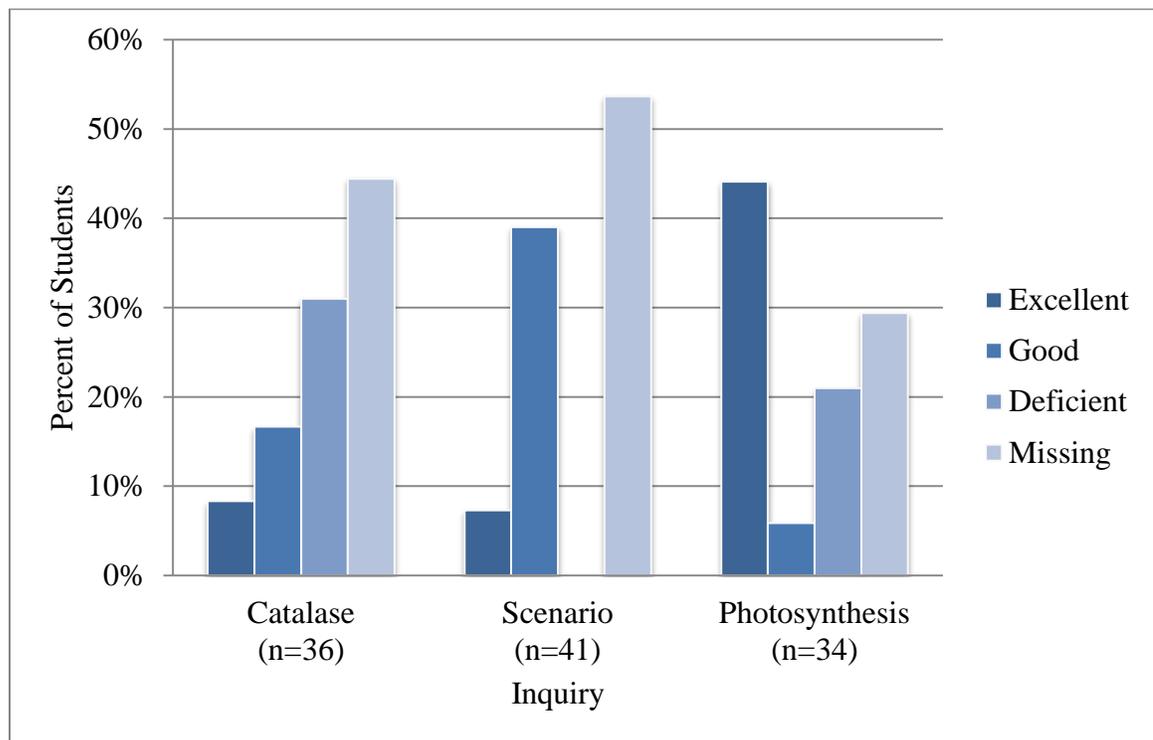


Figure 5. Use of scientific theory in conclusions scores for inquiry reports, ($N = 44$).

Comparison of students' pre- and post-treatment Intervention Surveys indicated significant positive differences (all $p \leq 0.05$) in students' feelings of ease in biology, in using technology and in designing, conducting and reporting controlled experiments (Table 3). Specifically, more students agreed that they could design and set up an

experiment and that they knew how to use science theories when explaining their own research. For instance, on the pre-treatment open-ended survey questions one student wrote, "Given freedom to make my own experiment terrifies me. I need exact instruction on what to do." Similarly, another wrote, "I really don't like doing labs, I always freak out because I think I am going to mess things up the whole time." Whereas on the post-treatment survey a student said, "I like being able to create experiments and learn from my mistakes." Another student wrote, "This class is fun, the importance is on how we learn. Keep doing it." By the end of my project significantly more students agreed they had experience writing a report and building tables and graphs using a computer (Table 3). However this did not necessarily translate into enjoyment for all students. On the post-treatment open-ended questions one student wrote, "I dislike writing conclusion and procedures and stuff like that." By the end of my project, significantly more students disagreed that they were uneasy in biology and did not want to be there and more students agreed they usually liked biology ($p = 0.07$). On the pre-treatment open-ended questions one student wrote, "I'm not very good at science, it's not my favorite thing to do." Another wrote, "I don't like working in groups." Whereas on the post-treatment open-ended questions many students wrote comments similar to this one, "This class was my favorite this year, but try to finish every chapter in the book." Attitudes about learning not directly tied to science were unchanged (all $p \geq 0.10$).

Table 3
Intervention Survey Questions, Pre and Post-Treatment Differences (N = 44)

Survey Question	Question Focus	Degrees of Freedom	Fisher <i>p</i> -value
18. I know how to set up an experiment by myself.	Skill	4	0.050
19. I could design an experiment to answer a question that was given to me.	Skill	4	0.045
21. I have used a computer to write an important report.	Skill	4	0.038
22. I know how to use Excel or other software to make data tables and graphs.	Skill	4	0.005
25. I know how to use scientific theories and information when explaining my own research and experiments.	Skill	4	0.002
36. I feel uneasy in biology and do not really want to be there most of the time.	Attitude	4	0.007

On the Skills Self Confidence Survey of the 16 inquiry skills sampled students had a significant gain in confidence on 12 skills (all $p \leq 0.05$). Students gained confidence in recognizing and researching a problem, developing a question, forming hypotheses, and defining variables. Nearly statistically significant was students' gain in confidence in designing experiments ($p = 0.058$). Students' confidence was not significantly changed in interpreting results or in recognizing or designating an experimental group (all $p \geq 0.24$). Students started with high levels of confidence on these factors and this remained unchanged from the beginning of this project to the end.

INTERPRETATION AND CONCLUSION

This project provided evidence that student-designed inquiry supported with the CLER rubric as scaffolding for data analysis and critical thinking can lead students to communicate their science findings clearly and logically. Over the course of this project, students improved in constructing tables and graphs. They also improved in forming arguments for their inquiry reports by supporting their claims with evidence and scientific theory. When I examined the evidence from this project I decided to extend this approach to all my biology classes not just honors biology.

Students improved in producing computer-generated tables in Word that were numbered and captioned correctly, had properly titled columns with correct units, and had accurate data. Students created increasingly sophisticated graphs that had proper labels for axes, captions, legends and data displays. Initially students struggled with creating tables in Word and graphs in Excel. For most students, this was a new undertaking and one that challenged them. Peer to peer mentoring was invaluable in improving students' computer skills. I reflected that for the coming school year I needed to create lessons that walk students through a series of table and graph constructions with data sets that I provide. I thought this could help prepare students in advance for analyzing their own data in tables and graphs.

Students became more adept at designing and conducting their own inquiries and their skill in critical thinking about what happened in their own experiments improved. Students developed markedly in providing a clear and accurate claim statement and in using data as evidence in the conclusions of their inquiry reports. Their improved dexterity with weaving claims and data together reflected their deep involvement in and

thus understanding of inquiry. Students encountered glitches in their research and were often frustrated, but ultimately they would articulate their own solutions. The didactic process was difficult for students accustomed to scripted inquiry but the student-designed inquiry process gave them better insight into the causal relationships among variables. I have planned to continue having students design inquiry investigations. I decided, some of those investigations will be true controlled experiments as in this project and others will be correlational observations or field studies.

Students improved at underpinning their claims and evidence with scientific theory but almost half of students had deficient or missing scientific explanations on their final inquiry report. At first students did not understand that inquiry reports' conclusions should explain results in light of scientific theory. Students tossed in bits of science theory without checking the relevance or simply left scientific explanation out altogether. Even with the CLER rubric, this was a difficult area for students because their science backgrounds were limited. It was challenging for them to filter just the right scientific nuance from the overwhelming stream of information available in textbooks and on the Internet. Also, some students left this step off because it *was* challenging. Students needed much more scaffolding in this area than I provided in this project. Students needed practice in using science content they had studied to explain the results of investigations. Practice would have prepared them for attaching science models as arguments in their conclusions.

This project provided evidence that the use of inquiry and authentic data analysis impacts student attitudes toward science. Surveys showed that over the course of the project students believed they had gained in ability to design and set up experiments and

use technology to write and produce tables and graphs. They also perceived gains in using scientific theories to explain their own research. Students' perceived a higher rate of liking biology and highly statistically significant was students' perceived gain in feeling at ease in biology class. I decided that in the next school year I would like to explore how student-designed inquiry can be used to make science more relevant, interesting and motivating for students that exhibit performance avoidance behaviors. The honors biology students that participated in this project had objectives for their learning that helped them succeed. I thought many students not in honors biology that are less diligent about their learning might find designing their own investigations interesting and thus motivating.

This project provided evidence that student-designed inquiry and authentic data analysis impact students' confidence in science skills. Students' gained in self-confidence in researching a problem and defining variables. Students gained in confidence in these skills by using them. There was no vocabulary practice or quizzes on the terminology of investigative design. Students shored up their understanding and increased their confidence in their science skills by designing their own research and by writing conclusions using data that was well organized in tables, analyzed with graphs and communicated through clear claims supported with evidence and placed in the context of science theories. Students' self-confidence remained unchanged on facets of experimental design where students started the year with high levels of self-confidence.

VALUE

Over the course of this capstone project there were three important changes in my teaching that I wish to continue and improve upon. The first of these was the increased amount of inquiry used in instruction. Second was the detailed scaffolding in the CLER rubric used to support students' critical thinking and written expression. Third was surveying students about their skills, knowledge, attitudes and self-confidence.

First of all, during this capstone my students had more opportunities and time to work collaboratively and creatively while developing and conducting their own inquiries than I usually allocate. To align the students' inquiries with curriculum I had provided the general topics. I decided an instructional goal for the next school year would be to add more opportunities for students to design and conduct inquiries and to let students select their own topics. Additionally, I decided to extend student-designed inquiry to my general biology classes in the coming school year.

Secondly, scaffolding with the CLER rubric was used to specify expectations for writing the results and conclusions of students' research reports. In the past, I gave students headings for these sections of their reports with brief descriptions of my expectations. Now, I plan to give students more specificity so their performance targets are even clearer. I plan to include additional scaffolding for students that want to go farther than the minimum requirements in the analysis of their data by giving them additional scaffolding for analyzing data in Excel.

The third area of change in my teaching involved using surveys to get to know my classes. I decided for the next school year to continue to seek student feedback through Likert style and open-ended questions so I can make adaptive instructional and

management corrections. I decided to use surveys more frequently and to share results with students at the beginning of each quarter. The results of this project suggested that surveys could help students to think about what they are learning, how they feel about it and consider what is motivating their personal learning strategies. I thought that frequent surveys with immediate feedback for students and me, could make the learning experience more personal and relevant for my students.

In summary, I determined that a professional goal was to increase students' opportunities for self-designed inquiry. A second goal that emerged was to provide curriculum-aligned rubrics for constructing inquiry reports using critical thinking and technology. Finally, I decided that I would frequently survey students and share the results with them along with any instructional adaptations that I plan to make based on their input.

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APPENDICES

APPENDIX A

CLER RUBRIC

Name _____ Class _____ Group _____ Date _____

Claim Evidence Reasons-----“Make it perfectly C.L.E.R.”				
Element	Excellent Proficient, keep polishing.	Good Developing, add missing details.	Deficient Unclear and/or missing parts.	Missing Missing goal, complete work.
<u>Claim statement</u>				
*Clearly states what your research found. *Gives relationship between manipulated and responding variables. *Correct grammar and punctuation. *Powerful direct language.				
<u>Evidence</u>				
*Use responding variable results (e.g. averages) across range of manipulated variable. * Use responding variable results for all critical or interesting values. *Clarify how the data relate to your claim by explaining the trend or relationship. * Relate non-				

numeric observations to claim.				
<u>Reasoning</u>				
<ul style="list-style-type: none"> *Compare your results to scientific models or theory. *Describe how your results are consistent or inconsistent with theory. *Explore alternative explanations for your results. 				
<u>Table</u>				
<ul style="list-style-type: none"> * Computer generated. *Columns titled, units given. * Numbered and captioned above. *Data correct and averages given. 				
<u>Graph</u>				
<ul style="list-style-type: none"> *Computer generated. *Axes titled. *Units given. *Numbered and captioned below. 				

(Adapted in part from Scoring Rubric for a Conclusion, Science Assessment Development Team, Office of Superintendent of Public Education, Washington State.)

APPENDIX B

INTERVENTION SURVEY

Intervention Survey

1. The most important thing to me in this class is learning.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

2. The most important thing to me in this class is to avoid looking dumb and feeling stupid.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

3. The most important thing to me in this class is to compete and get the highest grades.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

4. If the work in this class gets to hard, I will not put in extra effort.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

5. If the work doesn't seem important or fun, I probably won't do it.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

6. I do not like to ask for help even when I don't know what is going on in class.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

7. I want to work hard to improve my skills.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

8. I would cheat on a test if I did not understand the questions.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

9. I will keep asking questions or studying until I understand hard concepts.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

10. The best part of success is showing others what I can do.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

11. I would rather guess on a problem than ask questions.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

12. If I make mistakes, I will keep trying.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree

13. Making mistakes shows that you do not have ability.
 - a. Strongly disagree
 - b. Disagree
 - c. Undecided

- d. Agree
 - e. Strongly agree
14. I can be creative in science and use my own thinking.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
15. I do not want to look like I have less ability than other students.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
16. Taking tests makes me nervous.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
17. I enjoy taking tests.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
18. I know how to set up a scientific experiment by myself.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
19. I could design an experiment to answer a question that was given to me.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
20. I have research skills that would help me to find out background information.

- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
21. I have used a computer to write an important report.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
22. I know how to use Excel or other software to make data tables and graphs.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
23. I am good at using data as evidence when I write up my conclusions to research.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
24. I have experience presenting and discussing my scientific research and experiments with all my classmates.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
25. I know how to use scientific theories and information when explaining my own research and experiments.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
26. When given data in a table or graph, I can find the patterns and relationships between the variables.
- a. Strongly disagree

- b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
27. If given a hypothesis or a question and a materials list, I can design the procedures for an experiment.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
28. I learn best by reading, studying and taking a test.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
29. I learn best by discussing and working on problems with other people.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
30. I learn best by doing things and developing a product.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
31. I learn best if I know exactly what is expected of me.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
32. I learn best if I have some freedom to try different things, even if I make mistakes.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree

- e. Strongly agree
33. I usually like biology.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
34. I do not like doing biology experiments.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
35. I feel relaxed and ready to be interested in biology.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
36. I feel uneasy in biology and do not really want to be there most of the time.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
37. I can see a purpose for studying biology.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
38. I expect to learn new things in biology.
- a. Strongly disagree
 - b. Disagree
 - c. Undecided
 - d. Agree
 - e. Strongly agree
39. What do you like about learning science?

40. What do you dislike about learning science?

41. What other things would you like me to know?

(Adapted in part from Elliot and Church (1997), *Journal of Personality and Social Psychology*)

APPENDIX C

SELF CONFIDENCE SURVEY

Course-Related Self-Confidence Survey

*Kinds of Skills and Understanding**Self-Confidence in Your Ability to Use Them*

1	Recognize the background observation (problem).	None	Low	Medium	High
2	Research additional information about the observation (problem).	None	Low	Medium	High
3	Create a research question based on information gathered.	None	Low	Medium	High
4	Form a hypothesis that is based on the research question.	None	Low	Medium	High
5	Form a hypothesis containing the manipulated and responding variables.	None	Low	Medium	High
6	Recognize or designate the manipulated variable .	None	Low	Medium	High
7	Recognize or designate a responding variable .	None	Low	Medium	High
8	Recognize or designate an experimental control .	None	Low	Medium	High
9	Recognize or designate an experimental group.	None	Low	Medium	High
10	Distinguish an experimental control from controlled variables .	None	Low	Medium	High
11	Recognize controlled variables .	None	Low	Medium	High
12	Design an experiment to test a hypothesis.	None	Low	Medium	High
13	Write clear and complete procedures .	None	Low	Medium	High
14	Collect data and observations as results.	None	Low	Medium	High
15	Interpret the meaning of the results.	None	Low	Medium	High
16	Form conclusions about the original question and evaluate the hypothesis based on results .	None	Low	Medium	High