INQUIRING INTO MEASUREMENT ERROR

IN THE SCIENCE LABORATORY

by

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ABSTRACT

High school students often struggle with accurate data collection in the science laboratory. This study examined the effects of inquiry-based laboratory learning experiences on student ability to recognize the limited precision of measurements, ability to see error, manipulative ability in using laboratory instruments and commitment to accuracy. Results indicate increased student ability to see and correct error as well as improved understanding of error.

INTRODUCTION AND BACKGROUND

Project Background

International Community School is a private, international, college preparatory school in Bangkok, Thailand, which follows an American style curriculum. I have taught introduction to chemistry and physics, a ninth grade course, at International Community School for the past five years. This class studies physical science with units on motion; forces and energy; chemical interactions; electricity and magnetism; and sound and light. Each unit includes a laboratory component.

This study involved four classes with a total of 83 students. Class sizes of 15 to 25 students per class are typical for high school classes at International Community School. The school admits 50% Thai students with the rest of the student population coming from many parts of the world. The nationalities of my students were typical of the school population according to the International Community School Bangkok Introduction and Profile (2010) with 57.8% Thai, 10.8% American, 9.6% Korean, 7.2% Indian, 4.8% Taiwanese, 2.4% each: English, Japanese, and Canadian, and 1.2% each: German and Malaysian (Class List 2010-11, 2010). Unpublished intranet document. The diversity does not carry over to the socio-economic status of the families, the great majority of which are upper-middle class. Business professions account for 72% of parent occupation. The majority of these students have learned English as a second language, and although only seven students are currently in the ESL program, a number continue to struggle with English language.

The introduction to chemistry and physics course is a required course for every ninth grade student. This provides a potential opportunity for every high school student to develop foundational understanding of science principles and skills for the laboratory learning experiences in this class. I am inspired to build up this foundation in order to lead students to richer laboratory experiences throughout their high school years and beyond.

Throughout my experience teaching Advanced Placement Physics, physics and introduction to physics and chemistry, I have witnessed high school students at all levels struggling with data collection in the laboratory. Students will make an appropriate data table but then turn their attention toward obtaining numbers to fill each box of the table without considering the significance of those numbers or whether they represent reasonable measurements. Some students discover they have unreasonable data only after they have put away their equipment. I expected inquiry-based laboratory learning experiences to encourage students to actively look for error throughout the entire process, notice unreasonable data, become aware of strategies for dealing with that error and develop manipulative skills that will result in less error.

Focus Question

Concern over student struggles with data and accuracy led me to my primary focus question: How will inquiry-based laboratory investigations, rather than traditional laboratory investigations, affect my students' ability to recognize the limited precision of measurements and ability to see error? In addition, I examined the following sub-questions: Will the use of inquiry-based laboratory investigations affect student manipulative ability in using laboratory instruments? Will the use of inquiry-based laboratory investigations affect student commitment to accuracy?

CONCEPTUAL FRAMEWORK

"Since the late 19th century, high school students in the United States have carried out laboratory investigations as part of their science classes. Educators and policy makers have periodically debated the value of laboratory learning experiences in helping students understand science, but little research has been done to inform those debates or to guide the design of laboratory education" (National Research Council, 2005, p. 1). According to the National Research Council, "laboratory experiences provide opportunities for students to interact directly with the material world (or with data drawn from the material world), using the tools, data collection techniques, models, and theories of science" (p. 31). Also identified were the following learning goals: "enhancing mastery of subject matter; developing scientific reasoning; understanding the complexity and ambiguity of empirical work; developing practical skills; understanding the nature of science; cultivating interest in science and interest in learning science; and developing teamwork abilities" (p. 3). This provides the context to identify whether a given activity is a laboratory learning experience which has validity in accomplishing the goals of science education.

Well-designed practical laboratory work has the potential to motivate students and to support deeper learning of concepts, manipulative competencies, and cooperative approaches to learning (Moni, 2007). Research comparing students working in the laboratory with students exposed only to demonstrations or computer simulations found that students who actually performed manipulations in the laboratory were more successful on evaluations of their skills than students exposed to non-laboratory methods (Demeo, 2005). Successful laboratory learning experiences allow students to practice basic manipulative skills and, preferably, to receive immediate feedback (Moni, 2007).

Moni (2007) described a strategy to teach and assess laboratory skills in which students must accomplish core tasks. Students are given a standard operating procedure, and after an opportunity to practice, are assessed on their ability to perform a specific skill. A trained lab assistant or teacher records the student skill level and provides immediate feedback and further guidance as needed (Moni, 2007). This provides two critical ingredients for promoting manipulative and observational laboratory skills, or process skills: identifying the reasons that students make a mistake, followed by remedial help for students to avoid repeating the same mistake in the future (Goh, Toh, & Chia, 1989). This process helps students develop the manipulative skills and experience needed to meet the employment-based requirement of knowing how to complete relevant skills–not merely know about them– which has been described as an information gap between old and new academic competencies (Moni, 2007).

The National Research Council (1996) describes inquiry in science education as a multifaceted activity involving performing independent research, making observations, proposing answers, and communicating results. Inquiry teaching and learning involves both content knowledge and abilities (Hofstein, Shore, & Kipnis, 2004). These are modeled by the inquiry standards developed by California that call for students to

> develop questions and perform investigations, select and use appropriate tools, identify and communicate sources of error, identify possible reasons for inconsistent results, formulate explanations, solve scientific problems, distinguish between hypothesis and theory, and achieve other goals related to laboratory learning. (National Research Council, 2005, p. 55)

Inquiry stresses the student's role as researcher and active investigator (Llewellyn, 2005). Teaching and learning through inquiry is characterized as a student-centered approach, in that the teacher acts as a facilitator or guide, not merely as the source of scientific information and knowledge (Hofstein et al., 2004). Inquiry is found to be effective with students at all levels as it engages them in their own learning (Wrinkle & Manivannan, 2009).

In the earlier half of the 20^{th} century, the development of physical laboratory skills was seen as something to be practiced independently of conceptual learning, but there is evidence of positive outcomes by integrating mental involvement with learning physical skills (Demeo, 2005). Inquiry experiences in the laboratory are especially effective when integrated with the concept being taught (Hofstein, Shore, & Kipnis, 2004). College students who summarized laboratory procedures in their own words worked faster and spent less time in lab than other students who copied the procedure in their notebooks (Pickering, 1987). These studies show the benefit of students being stimulated to think through the procedures before they get to the laboratory. Also, introductory college chemistry students exposed to inquiry experiences possessed greater manipulative abilities than those students who performed structured non-inquiry laboratory activities (Demeo, 2005). One technique for integrating conceptual learning into the laboratory learning experience is by incorporating small group work, referred to as cooperative learning, in a pre-laboratory setting. Groups of three students answer questions concerning comprehension of the experiment, experimental procedures, and the prevention of common mistakes for a pretest grade (Fleming, 1995).

Laboratory notebooks can be an effective tool in improving student data by providing a method that allows them to make meaningful claims based on well-documented, high-quality data (Roberson & Lankford, 2010). These notebooks can also help students place science in a meaningful context (Edelson, 1997). With practice, students will understand the link between data, evidence and claims thus improving their scientific literacy (Roberson & Lankford, 2010).

Demeo (2005) considered the types of errors encountered in laboratories and encouraged discussion of random errors in the classroom because it helps students view experimental values with skepticism and respect. The historical practice of scientists building their own instruments allowed them to understand the capabilities and limitations of those instruments and thus the potential for error (Resnick, 2000). An additional way to facilitate this understanding is to provide the opportunity for students to calibrate instruments in the context of a scientific investigation (American Association for the Advancement of Science, 1993). To further aid students in developing a mature understanding of error, the teacher should not evaluate student data during lab time (Demeo, 2005). This causes the learners to face the realization that they have to trust their data. They must realize that they must make an argument for trusting what they have observed and measured. To succeed, the learners must ask themselves and their teacher about specific areas that may affect their results. “As both doubt and certainty are experienced, the manipulations that [the students] have made become emotional, personal events…. It is in this sometimes tumultuous experience—the quest for “good” data—that students experience some of what more mature scientists experience” (Demeo, 2005, p. 323). Such investigations that approximate authentic science will lead students to form a reasonably accurate picture of the nature of scientific inquiry (AAAS, 1993).

METHODOLOGY

Students participated in an introductory laboratory learning experience during the first week of school in which they were given a variety of laboratory instruments and asked to make seven measurements. This exercise introduced them to the types of scientific instruments they would be using to make measurements, techniques for safe and accurate use of these instruments and expectations for acceptable ranges of error. Each of the student-recorded measurements was evaluated for accuracy using a four point scale.

Forty-two students were randomly selected from my four classes to complete the Practical Individual Measurement Test, an individual assessment that asked students to make measurements using three familiar laboratory instruments: a ruler, a graduated cylinder and a stopwatch (Appendix A). All three of these instruments were introduced to the students in the introductory laboratory learning experience in week one. During The Practical Individual Measurement Test, a student was seated in front of a ruler, a 10 centimeter tall drinking cup, a 100 milliliter graduated cylinder containing approximately 50 milliliters of water, a stopwatch and a 17 centimeter long pendulum. I then asked them to give me the most accurate measure for the height of the drinking cup. Next, I asked them to give me the most accurate measure of the volume of water in the graduated cylinder. Then, after reminding the students that one full swing over and back again is one period, I asked the student to give me the most accurate measure of six periods of the pendulum. After recording each answer, I gave feedback regarding what they did well and what they could improve to make their answer more accurate and precise before moving on to the next measurement. The Practical Individual Measurement Test was used with a corresponding Practical Individual Measurement Test Rubric to provide a baseline to assess student development in ability to perceive error, manipulative ability and commitment to accuracy (Appendix B). These were organized by most commonly missed skills and range of error for the analysis section. Uncommon errors were also noted.

I administered the Student Confidence in Measurement Survey prior to the treatment phase to assess student confidence in laboratory measurement when using four specific laboratory instruments and independently measured laboratory data. In addition, the survey assessed students' practice of established laboratory techniques and confidence in their ability to perceive error (Appendix C). Students were asked to indicate the degree of agreement to ten statements using a four-point Likert scale that ranged from *strongly agree* to *strongly disagree*. The five-month treatment phase consisted of six inquiry-based laboratory learning experiences (Appendix D). The Student Confidence in Measurement Survey was given again at the end of the treatment period. Percents of response were calculated and the data was analyzed for the most common responses as well as change in student confidence. Categories were combined to compare students who indicated *agreement* and *disagreement* for each question and a two-sample t-test was performed with the pre-treatment and post-treatment data to test for significant change in student confidence.

The Student Confidence in Measurement Survey data were used to separate students by level of confidence in making accurate measurements when using a meter stick. The percentage of students observed correctly aligning a measured object with the zero-mark of a ruler on the pre-treatment Practical Individual Measurement Test was calculated separately for each of the four levels of confidence. Similarly, pre-treatment levels of confidence in making accurate measurements when using a graduated cylinder were used to separate students into four groups. The percentage of students observed correctly measuring the volume of water in a graduated cylinder from the bottom of the meniscus was calculated for each of the four groups. These data were examined along with post-treatment data for correlation between student confidence and correct procedural technique.

The six inquiry-based laboratory learning experiences consisted of the following laboratories. The Density of Clay Lab allowed students to choose from about 20 laboratory instruments to measure the density of a lump of clay using two different methods, and then report a most accurate value for that volume. The Inclined Plane – Simple Machine Lab asked students to compare the ideal and actual mechanical advantage when dragging a wood block up a ramp inclined at various angles. Students balanced unequal stacks of coins on a meter stick acting as a lever, and then measured the distance of each stack from the fulcrum in the Lever Lab. The Pendulum Lab asked students to experiment and record detailed data that could verify whether changes of displacement, mass of the bob, or length of the pendulum had the greatest effect on its period. The Temperature Change in Chemical Reaction Lab allowed students to make various combinations of substances in a calorimeter to produce endothermic reactions, exothermic reactions or no reaction and then measure the greatest change in temperature of the substances. Students made a simple hydrometer out of a lump of clay and a drinking straw, then constructed a scale which they used to measure the density of unknown solutions accurate to the 0.005 gram per milliliter in the Hydrometer Lab

Methods used to measure students' ability to perceive error throughout the treatment period included these six inquiry-based laboratory learning experiences. A performance assessment component of each of these assessed students' abilities to develop questions and perform investigations, select and use appropriate tools, identify and communicate sources of error, identify possible reasons for inconsistent results, formulate explanations, and solve scientific problems. I supplemented my actual observations with audio recordings and both were incorporated into my field notes. These notes were categorized according to the six topics listed above and analyzed for effects on accuracy of student data.

Each student was required to keep a laboratory notebook throughout the year. This provided students with a sense of ownership of their laboratory learning and data and allowed students to refer back to procedures used in previous laboratory learning experiences. These notebooks were introduced after the first inquiry laboratory investigation. Students were instructed to collect data in a data table on a separate sheet of paper and then, in the following class, were presented with the components and proper format of the laboratory notebook entry. They worked together with their lab group to construct sample lab notebook entries based on this first inquiry laboratory investigation. These notebooks were collected after each laboratory investigation for assessment of recorded raw data, calculations, and any identified sources of error using the Laboratory Notebook Rubric (Appendix E).

Following each of the inquiry laboratory learning experiences, two or three students from each of four classes were interviewed using the Post Laboratory Interview (Appendix F). The first five interview questions were slightly modified each time to make them relevant to the specific laboratory learning experience. Students were selected so that throughout the treatment phase, each consenting student was interviewed once. 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 (Appendix G & H). Students were asked to explain the methods they used to make measurements and their reasons for using those methods. They were also asked to identify sources of error and difficulties they faced in making accurate measurements. These data were analyzed for student ability to perceive error and for commitment to accuracy. Student misconceptions and evidence of progress toward taking and reporting accurate laboratory measurements were also recorded. Formative feedback from the interviews, field notes and Laboratory Notebook Rubric was communicated with the students after each laboratory session.

In addition to the regular interviews, a Hydrometer Five Minute Assessment was administered following the final laboratory session. Students were asked to identify three things they learned about measurement from the laboratory as well as questions they still had. Student responses were considered alongside those from the Post Laboratory Interview. Initially I had not planned to do this assessment; however after seeing how much the students learned, I wanted to have a more complete record of student progress and wanted the students to receive feedback about what they and others had learned.

The final laboratory session was followed by the administration of the post-treatment Practical Individual Measurement Test and Student Confidence in Measurement Survey. The results were compared with those of the pre-treatment Practical Individual Measurement Test and the pre-treatment Student Confidence in Measurement Survey in order to determine if there was an increase in ability to perceive error, commitment to accuracy and development of manipulative skills relating to accuracy and error in the laboratory. The sources used to collect data that answered my research questions are found in the Data Triangulation Matrix (Table 1).

Table 1
Data Triangulation Matrix

	Ability to perceive error/ Consciousness of inherent imprecision of measurements	Manipulative skills ability	Commitment to accuracy
Student Confidence in Measurement Survey	X		
Practical Individual Measurement Test	X	X	X
Student Interviews	X		X
Teacher Field Notes		X	X
Student Laboratory Notebooks	X	X	X
Performance Assessment of Lab Skills for Each Lab	X	X	

DATA AND ANALYSIS

Ability to See Error

The pre-treatment Student Confidence in Measurement Survey (Appendix C) results indicated high overall student confidence in their ability to report accurate measurements using thermometers, stopwatches, graduated cylinders and meter sticks as indicated by their selection of *agree* or *strongly agree* for the corresponding question (*N*=81) (Figure 1). The highest area of confidence was in using a meter stick (89%), followed by thermometer (81%), stopwatch (77%) and graduated cylinders (63%). Students were observed making common errors during the Practical Individual Measurement Test that would considerably impact the accuracy of their measurements. The post-treatment survey indicated little change in most areas with the exception of measuring using a graduated cylinder. The meter stick remained the highest area of confidence at 93%, followed by the thermometer and graduated cylinder both 84% and the stopwatch at 75% (Figure 1).

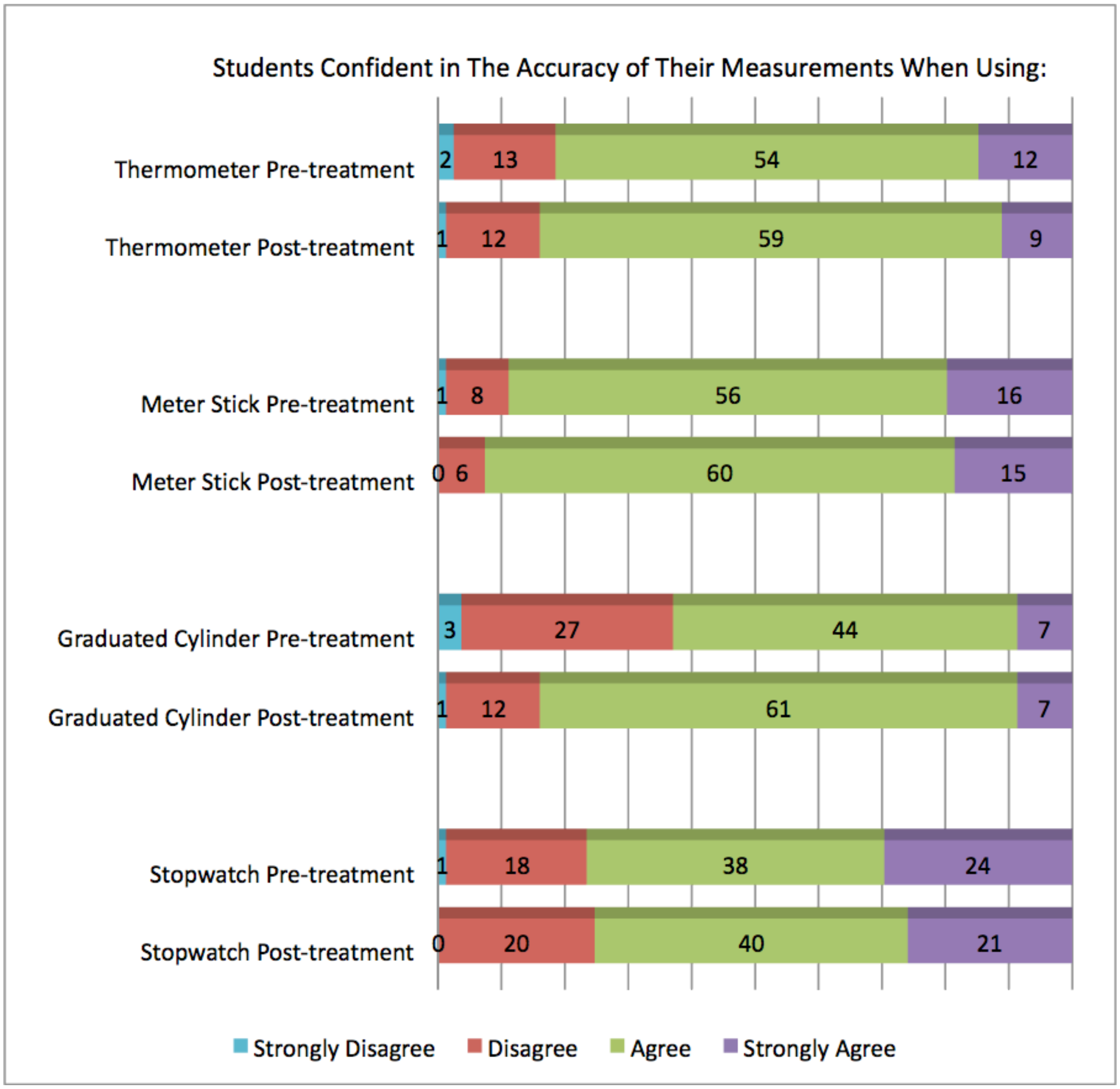

Figure 1.Selected Results from Student Confidence in Measurement Survey Pre-treatment and Post-treatment, (*N*=81).

Students were grouped by the pre-treatment levels of confidence in the accuracy of measurements taken with meter sticks. The percentage of students who were observed correctly aligning a measured object with the zero-mark on a ruler during the Practical

Individual Measurement Test was calculated for each of four groups. With the exception of the *strongly disagree* group, the percentage of students who were observed using the correct technique was near the average value of 64.3%. The *strongly disagree* group had 0% which can be explained by its having only one member (Table 2).

Table 2
Correlation between Student Confidence and Correct Procedural Technique when Measuring Length (N=42)

Student Confidence in Measurement Survey Response: I Can Measure Accurately with a Meter Stick	Percentage of students who correctly align object with zero-mark on ruler during Practical Individual Measurement Test.	
	Pre-treatment	Post-treatment
Strongly Agree	62.5% (*n*=8)	88.9% (*n*=9)
Agree	66.7% (*n*=30)	90.6% (*n*=32)
Disagree	66.7% (*n*=3)	100.0% (*n*=1)
Strongly Disagree	0.0% (*n*=1)	0.0% (*n*=0)
Total	64.3% (*N*=42)	90.5% (*N*=42)

Post-treatment data from the Practical Individual Measurement Test and Student Confidence in Measurement Survey were similarly examined and compared to the pre-treatment data. Ninety percent of students were observed correctly aligning the measured object with the zero-mark on the ruler during the post-treatment Practical Individual Measurement Test. No students selected *strongly disagree* on the post-treatment survey. A comparison of the three remaining groups found that none of these varied considerably from the average of 90.5% students using the correct technique (Figure 2).

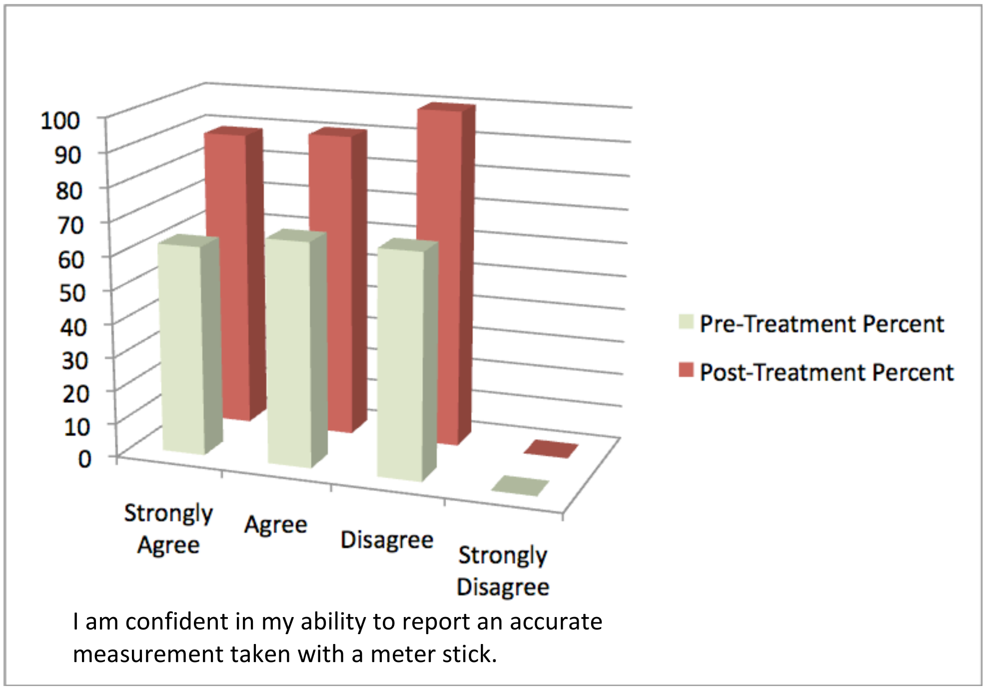

Figure 2. Students Who Correctly Aligned Measured Object with Zero Mark of Ruler on Practical Individual Measurement Test. Ranked by Confidence in Reporting an Accurately Measured Length.

The pre-treatment Student Confidence in Measurement Survey responses regarding graduated cylinders were used to separate students according to their four levels of confidence. The percent of students who correctly read the volume from the bottom of the meniscus was calculated and none of the four groups were found to vary considerably from the average of 33.3% students using correct technique (Table 3).

Table 3
Correlation between Student Confidence and Correct Procedural Technique when Measuring Volume (N=42)

Student Confidence in Measurement Survey Response: I Can Measure Accurately with a Graduated Cylinder	Percentage of students who correctly read volume measure from bottom of the meniscus in graduated cylinder during Practical Individual Measurement Test.	
	Pre-treatment	Post-treatment
Strongly Agree	50.0% (*n*=4)	80.0% (*n*=5)
Agree	26.3% (*n*=19)	71.9% (*n*=32)
Disagree	35.3% (*n*=17)	75.0% (*n*=4)
Strongly Disagree	50.0% (*n*=2)	100.0% (*n*=1)
Total	33.3% (*N*=42)	73.8% (*N*=42)

Seventy-four percent of students observed measuring volume on the post-treatment Practical Individual Measurement Test correctly measured from the bottom of the meniscus. The single student that selected *strongly disagree* did measure correctly giving that category 100%; however, none of the other three categories varied considerably from the average value of 73.8% (Figure 3). These data indicate that students who are confident in their abilities to measure with a meter stick and graduated cylinder have a similar occurrence of procedural errors as those who are not confident.

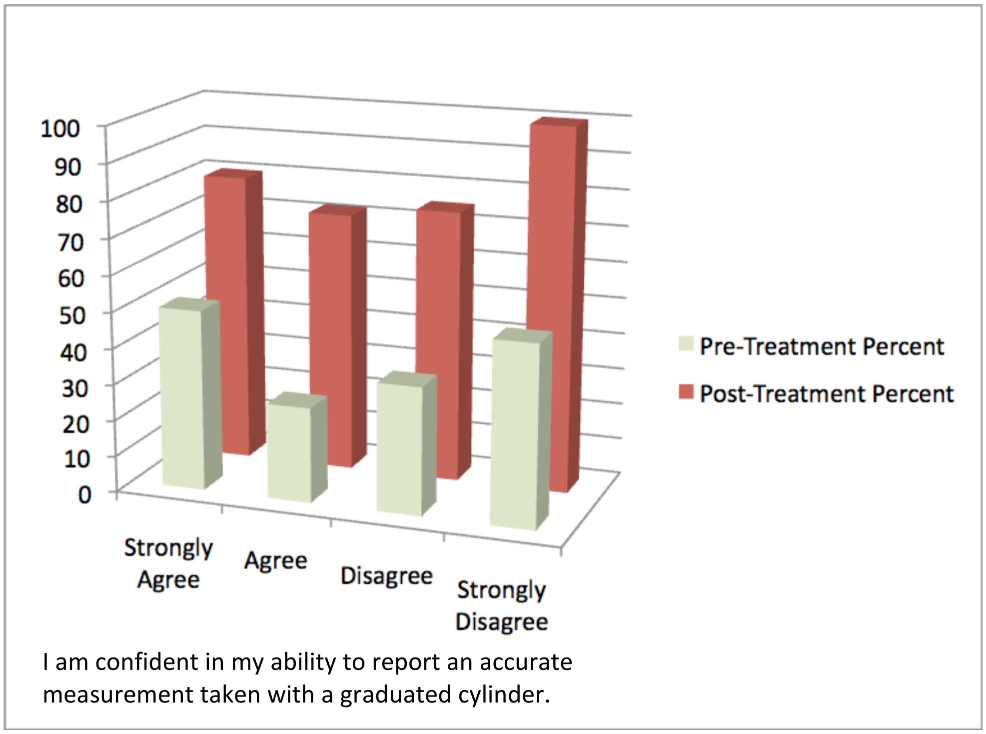

Figure 3. Students Who Correctly Measured Volume from the Bottom of the Meniscus on Practical Individual Measurement Test. Ranked by Confidence in Reporting an Accurately Measured Volume.

When asked on the pre-treatment survey to respond to the statement "When using a stopwatch, I can tell the difference between when I have measured accurately and when I have not," 35% of students disagreed, with 5% of those students indicating that they *strongly disagreed*. The post-treatment survey indicated that 25% of students disagreed with 1% indicating that they strongly disagreed. When categories were combined to compare students who *agree* and *disagree*, a two-sample t-test indicated that the number of students who felt they could tell when they had measured accurately post-treatment was significantly higher, $t(160) = 1.87$, $p = 0.032$, (N=81), The pre-treatment Practical Individual Measurement Test found that 58% of students correctly assessed the accuracy of their measurement when using a stopwatch (N= 42). Of the students who agreed that they could correctly assess their accuracy, 67% did in fact demonstrate that on the Practical Individual Measurement Test. This result can be compared to 46% of those who disagreed that they were able to correctly assess their accuracy. During the post-treatment Practical Individual Measurement Test, 81% of students correctly assessed the accuracy of their measurements (*N*= 42). This included 82% of students who agreed that they could correctly assess their accuracy compared to 78% of students who disagreed.

Five percent of students requested not to count their first measured value for time, but to allow them to measure a second time on the pre-treatment Practical Individual Measurement Test. The post-treatment administration of the Practical Individual Measurement test found 24% asked to measure a second or even a third time. Of these students, most were observed to have originally miscounted the six periods of the pendulum. One girl simply laughed after measuring the first time because she knew she was not even close. One of the students who asked to measure a second time on both the pre-treatment and post-treatment test had similar values each time. At the end of the pre-treatment test she said she had "proved" the accuracy of her measurement. Unfortunately, she had counted five and a half periods and not six, thus giving her the same amount of error both times due to her procedural error. On the post-treatment test she asked to repeat her measurement three times. Again she was confident and again, all three times, her measured times where short one half period.

When asked about sources of error in the pendulum laboratory investigation, one interviewed student indicated that they held the brass hanger being used as the pendulum bob vertically instead of holding it "at the same angle as the [pendulum's] string." He noted that, “When we let go, it made it kind of wobbly so that could cause error.” Other students indicated that error could result from timing the period of the pendulum since it was difficult to tell the precise point at which the pendulum changed direction at the end of a swing. Another student noted that at times the pendulum bob hit the base of the laboratory tables.

Commitment to Accuracy

The Hydrometer Five Minute Assessment which followed the final laboratory learning experience indicated 33% of the students assessed responded that they learned from this laboratory the necessity to be *accurate* or *exact* when measuring. For example, one second language student wrote, “We must measure things accurately in order to make the data stable.” Twelve percent mentioned that they must be *careful*, and another 5% indicated that they must be *precise*. As students could have been classified into multiple categories, these collectively account for 47% of all students indicating on this instrument an obligation to measurement accuracy.

Twenty-two percent of students indicated that measuring accurately was difficult. The majority wrote that it was *hard* or *not easy* to measure. Some of these students were more specific and wrote that it takes *patience*, *concentration* or *time* to measure accurately. One student responded with all three.

Another common theme on this assessment was an awareness of the need to double check measurements. Eighteen percent of students indicated that measurements must be read more than one time with responses like, “Nothing absolute can come out of measuring once.” Responses such as, “Have people double check your measurements just to make sure” were common with 12% of students indicating they would double check their measurements with someone else. This was also indicated by student comments during the Practical Individual Measurement Test. Students said they would check their measurements in a laboratory setting with 31% commenting that they would measure more than once. I asked one student if he thought his measured value for time was accurate and his response was, "I wouldn't know until I do it again because if I do it again, I can see if it's the same… No, let me do that again." Students also indicated that they would have a friend check their measurements with one student lamenting the fact that there was no one to double check her measurement.

Students reported they have more than one student read the measurements in the laboratory, with just 11% indicating on the pre-treatment administration of the Student Confidence in Measurement Survey that they *disagreed* with the statement, “In a lab group I usually have more than one person read the measurement on the graduated cylinder.” One of the students who disagreed indicated that he *strongly agreed* that he could take and record accurate measurements with each of the four laboratory instruments listed. He also *agreed* that he liked taking measurements in the laboratory. At the post-treatment phase, 6% *disagreed* with the above statement and 1% *strongly disagreed*. When asked, the student who *strongly disagreed* said that he selected this response because, although someone else in the group would make sure that more than one student checked measurements, it was never him.

In the laboratory, many students were observed taking great pains to be precise in their measurements and to help each other modify technique to get more accurate data. When my students knew there was an expectation of accuracy that was being assessed throughout the lab, there were indications that students were working hard to get accurate data. One laboratory learning experience required students to measure the height of an inclined plane. After assessing their technique and making suggestions, I listened to the students as they continued working. I overheard one student talking to a lab partner after one measurement was made saying, “OK. Try this one, try this one!” Another group had one student making measurements and a lab partner anxious to know the results asked, “Jim, what is it?” This was followed by, “Jim, can you stand on the other side?” so as to allow her to try to read the meter stick at the same time. I also had to reprimand one girl who had climbed up onto the lab table to read a spring scale because two of her friends were already standing beside the table pulling and reading it. These are just a few examples of students taking pains to get accurate data.

Ability to See Limited Precision of Measurements

Students indicated causes and effects of limited precision of measurements on the Hydrometer Five Minute Assessment. One student commented that they came to realize that “mistakes can occur anywhere.” Another wrote, “There is no way anyone can have absolute measurement!” Many students mentioned rounding as one specific cause of error in their laboratory data. As one student put it, “You have to be precise, don’t round numbers too quickly.” Another limitation was using measurement instruments that were inaccurate. One student said, “Measuring with different rulers give different results, causing inaccurate measures and messing everything up.” Other specific sources of imprecision mentioned were student-made graduation lines on a hydrometer that were too thick or not straight.

Effects that students saw in their laboratory included a small imprecision in one measurement affecting the outcome of their experiment. One student said, “Inaccurate measurements, even small ones, can throw a project off.” Another student wrote, “If you get one variable off, then the measurements after that will get off to [sic].” Some students discovered imprecision as they worked in the laboratory which caused them to have to throw out their data and start over. One student wrote, “There can be a lot of mistakes [which cause us to] have to start almost all over.”

A number of students who accurately recorded the variables and conditions of their experiment in the procedure section of their lab notebook indicated a sense of hopelessness in reproducing those conditions during a follow-up period provided for students to complete their investigations. Students in one lab group asked me what they could do since they could not make the conditions exactly the same as in the previous period. I looked at their recorded data and told them that it appeared that they had recorded sufficiently detailed information in their procedures to allow them to set up their pendulum in the same way as they had previously. One student responded, “But no matter what, it is not going to be exactly the same.”

Manipulative Ability

In a pre-laboratory discussion session, students were asked what tool they might use to measure displacement of a pendulum. In each class, students decided that either a protractor or meter stick could be used to make an accurate measure of displacement. Two students interviewed indicated they selected to use the meter stick, and they struggled to accurately measure displacement because they found moving the pendulum caused the bob to rise up far above the meter stick. One student indicated in an interview that their group dealt with this difficulty by holding a ruler perpendicular to the meter stick and having the bob touch the ruler.

One lab group was trying to measure the volume of a lump of clay that was approximately 10 cubic centimeters. They had selected a 600 milliliter beaker to attempt to measure the change in volume of water due to the displacement of the clay. After putting the clay in, one student looked at the beaker and asked, "How are we supposed to tell?" Another member responded, "I told you we should have used the other one."

Student measured values on the post-treatment Practical Individual Measurement Test indicated an increase in accuracy and reduced range of error compared to the pre-treatment test. When analyzing the pre-treatment test of length, I considered one extreme outlier separately. When measuring the height of a 10 centimeter drinking cup one student held the ruler upside-down. She told me the height of the cup was 20.2 cm. When asked if she thought that seemed a little bit high, she checked her measurement a second time and instead reported 20.15 cm. With that outlier excluded, the median measure for length was below the true value by 0.04 cm on the pre-treatment test and

0.00 cm on the post treatment test. The pre-treatment standard deviation of 0.232 cm can be compared with the post-treatment value of 0.192 cm (Figure 4).

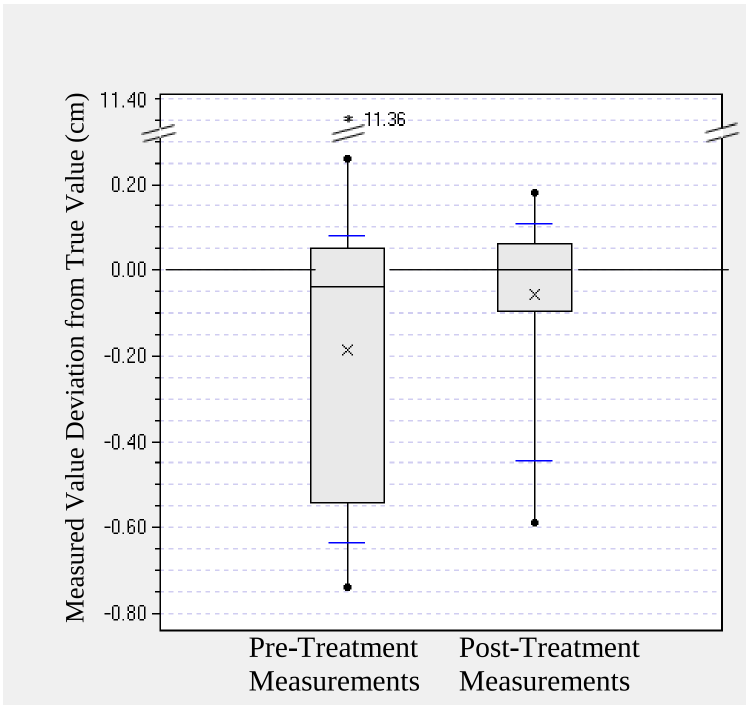

Figure 4. Deviation in Student Measurements of Length from True Value on Practical Individual Measurement Test, (*N*=42).

The student volume measurements of 50 milliliters of water had a median value that was 1.10 ml above the true value on the pre-treatment test and 0.65 above on the post-treatment test. The pre-treatment standard deviation was 1.78 ml while the post treatment standard deviation was 0.76 ml (Figure 5).

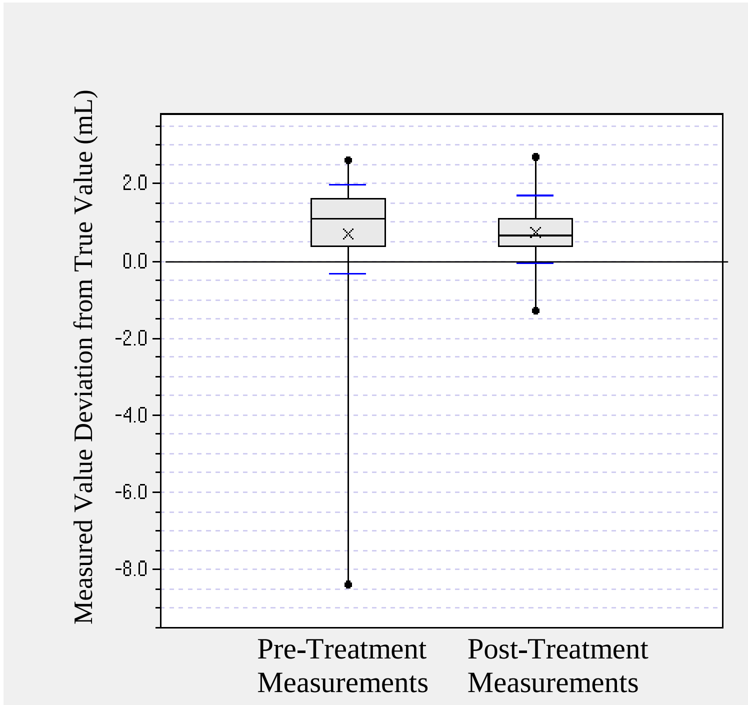

Figure 5. Deviation in Student Measurements of Volume from True Value on Practical Individual Measurement Test, (*N*=42).

Change in student measurements using a stopwatch were evidenced by a median value that was 0.18 seconds below the true value on the pre-treatment test and 0.02 seconds below on the post test. The pre-treatment measurements had a standard deviation of 0.70 seconds while the post-treatment measurements had a standard deviation of 0.36 seconds (Figure 6).

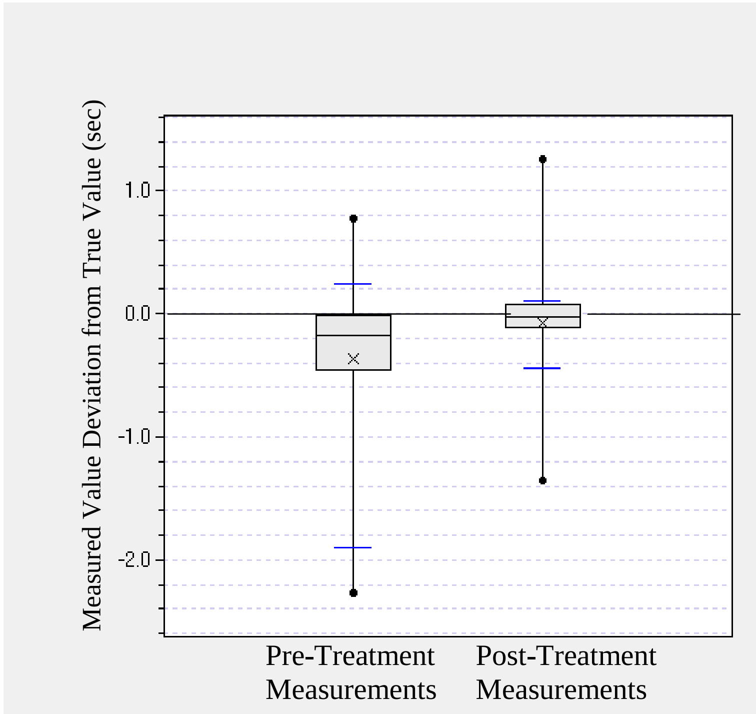

Figure 6. Deviation in Student Measurements of Time from True Value on Practical Individual Measurement Test, (*N*=42).

INTERPRETATION AND CONCLUSION

This study provides evidence that inquiry-based laboratory investigations were effective in increasing student awareness of measurement error. One example was measurement using stopwatches where 24% of students realized their error and asked to measure a second time to correct it on the post-treatment test compared to 5% on the pre-treatment test. Also in the laboratory room, students were observed correcting each other's errors.

Improvements in manipulative ability were reflected in decreased deviation of median measured value from the true value on all three parts of the post-treatment administration of the Practical Individual Measurement Test compared to pre-treatment showing that the average student made more accurate measurements post-treatment. Smaller standard deviation values at the post-treatment indicate that most students made improvements in measurement accuracy. Inquiry-based laboratory investigations gave opportunities to develop manipulative ability through experiencing consequences of error. Making and calibrating their own hydrometers, then using those to endeavor to gather accurate data revealed areas where students needed to develop their manipulative abilities. It also gave students a fairly complete picture of the many obstacles to making accurate measurements.

One surprising result was that students did not appear to be able to assess their own ability in measuring. This was true both at the pre-treatment and post-treatment phase as evidenced by the lack of correlation between their confidence in ability to record accurate measurements with laboratory instruments and their actual performance using those instruments on the Practical Individual Measurement Test. This may be an area for future development.

Student comments throughout the treatment indicated that inquiry-based laboratory investigations were effective in giving students experiences that mirrored authentic science. Evidence included student comments that gathering accurate data was hard work and took a lot of time, concentration, and patience. Other comments that indicate a mature understanding of the scientific process include those of one girl who wrote, “There isn't a stage when your [sic] completely sure of your measurements.”

Another student said, “Try to get [measured values] as accurate as possible, but don't keep trying to make it perfect.”

VALUE

The process of action research has led to significant changes in my teaching. I evaluate and modify my methods based on student feedback and let the students know how their feedback was used to change our classroom experience. Before using the action research model, I did not expect students to be able to give insightful feedback. I now realize how much better I can understand my students’ classroom experience through just a few 10-minute interviews or a short classroom assessment. In general students loved to be interviewed and felt edified by being included in the improvement process.

Increased awareness has led me to modify counterproductive practices. An example is laboratory investigation experiences where I tell students that they should collect quality data only and if necessary, leave the labs incomplete. Through notebooks and interviews I helped give students, and indirectly myself, greater accountability. I realized as time gets short, I often pressure students to make quick, imprecise measurements to finish up the investigation. This made me less critical of my students and helped me realize that I am to blame for some of the low quality laboratory data.

I have generally felt defeated as a teacher and that I had little of value to offer my school community. In this action research process, I learned how to develop an organized plan to identify and gain perspective on problems in my classroom, including research into best practices, development of a plan to deal with those problems and finally evaluation of the effectiveness of the treatment. This has made me feel I have something of quality to contribute. Confirmation has come from sources such as one validation team member who, when I was sweating over finishing this paper said, "My research was kind of bogus but you really have something here." Another member told me, "If your excitement about what you have been doing here is any indication, you have nothing to worry about." After discussing my project with an administrator, he approached me about doing a workshop for the science teachers at my school next year, then applying to present at the EARCOS conference, which will be held in Bangkok next March.

In addition to personal improvement, students have gained a better understanding of where error comes from and how it affects the results of their investigations. I expected many students had been getting little from investigative laboratory experiences, but interviews showed me that even second language learners and students who were less involved made gains which allowed them to answer high level questions and describe the laboratory activity accurately. Feedback also indicates that they have gained experience from inquiry-based laboratory investigations that mirrors authentic scientific investigations. This should prepare them well for future science experiences.

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APPENDICES

APPENDIX A

PRACTICAL INDIVIDUAL MEASUREMENT TEST

Appendix A
Practical Individual Measurement Test

Practical Individual Measurement Test

Length (Height)	Line up starting point correctly (Account for space at end of ruler)	Estimate to the 10th of mm	Measure at eye level (Looks at the ruler straight.)	Take time to observe carefully
Volume	Measure from top / bottom of meniscus	Estimate to the 10th of mL	Measure at eye level	Take time to observe carefully
Time Period	Starts with 0 (or counts full periods)	Reaction time	Doesn't lose count	Correctly assesses accuracy.

Name: ______________________ Block: ______________

APPENDIX B

PRACTICAL INDIVIDUAL MEASUREMENT TEST RUBRIC

Appendix B
Practical Individual Measurement Test Rubric

Practical Individual Measurement Test

Length (Height) Accurate Within: 0.05cm Good 0.10cm Average 0.15cm Below Average 0.50 cm Poor >0.50 cm Exceptionally Poor	-Manipulative Ability- Line up starting point correctly (Account for space at end of ruler) Yes / No	-Commitment to Accuracy- Estimate to the 10th of mm Yes / No	-Manipulative Ability- Measure at eye level (Looks at the ruler straight.) Yes / No	-Commitment to Accuracy- Take time to observe carefully Yes / No
Volume Accurate Within: 0.3 ml Good 0.6 ml Average 0.9 ml Below Average 2.0 ml Poor >2.0 ml Exceptionally Poor	-Manipulative Ability- Measure from top / bottom of meniscus Top / Mid / Bottom	-Commitment to Accuracy- Estimate to the 10th of mL Yes / No	-Manipulative Ability- Measure at eye level Yes / No	-Commitment to Accuracy- Take time to observe carefully Yes / No
Time Period Accurate Within: 0.1 sec Good 0.2 sec Average 0.3 sec Below Average 1.0 sec Poor >1.0 sec Exceptionally Poor	-Commitment to Accuracy- Starts with 0 (or counts full periods) Yes / No	-Manipulative Ability- Reaction time Yes / No	-Manipulative Ability- Doesn't lose count Yes / No	-Ability to Perceive Error- Correctly assesses accuracy. Yes / No

APPENDIX C

STUDENT CONFIDENCE IN MEASUREMENT SURVEY

Appendix C
Student Confidence in Measurement Survey

1) I am confident in my ability to report an accurate measurement taken with a thermometer.

   Strongly agree   Agree   Disagree   Strongly disagree

2) I am confident in my ability to report an accurate measurement taken with a meter stick.

   Strongly agree   Agree   Disagree   Strongly disagree

3) I am confident in my ability to report an accurate measurement taken with a graduated cylinder.

   Strongly agree   Agree   Disagree   Strongly disagree

4) I am confident in my ability to report an accurate measurement taken with a stopwatch.

   Strongly agree   Agree   Disagree   Strongly disagree

5) When I measure something more than once and I get different answers I know why they are different.

   Strongly agree   Agree   Disagree   Strongly disagree

6) In a lab group I will argue for the accuracy of my measurements.

   Strongly agree   Agree   Disagree   Strongly disagree

7) When using a stopwatch, I can tell the difference between when I have measured accurately and when I have not.

   Strongly agree   Agree   Disagree   Strongly disagree

8) In a lab group I like to take and report measurements.

   Strongly agree   Agree   Disagree   Strongly disagree

9) In a lab group I usually have more than one person read the measurement on the graduated cylinder.

   Strongly agree   Agree   Disagree   Strongly disagree

APPENDIX D

INQUIRY BASED LABORATORY LIST

Appendix D
Inquiry Based Laboratory List

1)	Density of Clay Lab	October 20, 2010
2)	Inclined Plane - Simple Machine Lab	November 8, 2010
3)	Lever Lab	November 15, 2010
4)	Pendulum Lab	December 3, 2010
5)	Temperature Change in Chemical Reactions Lab	February 21, 2011
6)	Hydrometer Lab	March 23, 2011

APPENDIX E

LABORATORY NOTEBOOK RUBRIC

Appendix E
Laboratory Notebook Rubric

	5	3	1	
Objective	Objective clearly stated in detail.	Objective is not clearly stated.		__x1=___
Procedure	Clearly and concisely outlines steps in own words. Analyst could easily repeat steps from procedure.	Outlines steps using own words. Difficult to repeat due to unclear or missing information.	Copied from assignment.	__x3=___
Data collection	Complete observations are recorded in a clear and orderly manner, with clear labeling.	Some observations are recorded in a clear and orderly manner, with clear labeling.	Observations are incomplete or not orderly.	__x3=___
Analysis	Data and observations concisely summarized. Any unexpected data is addressed and explored. Possible sources of error are discussed.	Data is summarized. Possible sources of error are discussed.	Data is not summarized, but simply listed or repeated.	__x3=___
Conclusion	Background knowledge and data from analysis are synthesized to draw a conclusion related to the objective.	Data is used in synthesizing the conclusion, but background knowledge is not.	Data summary is not used to synthesize conclusion.	__x2=___
Use of scientific language	Objective, scientific writing throughout document. Correct use of all terms.	Occasional use of nonobjective language.	Nonobjective language used throughout. Occasional informal language used.	__x2=___

Adapted from: http://www.nsta.org/highschool/connections/201001ScoringRubrics.pdf

APPENDIX F

POST LABORATORY INTERVIEW

Appendix F
Post Laboratory Interview

Density of Clay Interview Questions:
Name:

1. In this lab activity, how did you determine the volume of the clay?

2. What piece of glassware did you use to find the volume of clay using water?

3. What made it difficult to find the volume using water?

4. What could be some sources of error when measuring volume this way?

5. When you used the ruler to determine the volume of the clay did you get the same answer as when you used water? How did you decide what value to use to find density?

6. Did you feel you had enough time to work in the lab?
7. In a lab where you are running short on time, do you usually make quick measurements that might not be precise so you can get the lab done, or do you make careful measurements and leave the lab incomplete?

8. Which do you feel you should do?
9. Do labs help you understand the content of the chapter?
10. Is there anything else you would like me to know about your experience with this lab?

APPENDIX G

SUBJECT INFORMED CONSENT FORM

Appendix G
Subject Informed Consent Form

SUBJECT CONSENT FORM
FOR
PARTICIPATION IN HUMAN RESEARCH AT
MONTANA STATE UNIVERSITY

Inquiring into Measurement Error

Your child is being asked to participate in a research study of student ability in and commitment to collecting accurate and reasonable data in a science laboratory. This may be useful in developing their ability and commitment to accurate measurement in laboratory investigations throughout high school and beyond. As part of my ongoing professional development I am performing original research in my classroom with ninth grade students in Introduction to Chemistry and Physics class.

If you agree to allow your child to participate, he/she will be asked to complete a laboratory practical pretest and posttest related to measurement skills, complete a short pre/post laboratory measurement survey and to submit recorded lab data in your science lab notebook for analysis. All of these data collection instruments fall within the area of common classroom assessment practices.

Identification of all students involved will be kept strictly confidential. Most of the students involved in the research will remain unidentified in any way. However, individual students will be selected for interviews as representatives of their randomly assigned lab groups throughout the study. Nowhere in any report or listing will students' last name or any other identifying information be listed.

There are no foreseeable risks or ill effects from participating in this study. All treatment and data collection falls within what is considered normal classroom instructional practice. Furthermore, participation in the study can in no way affect grades for this or any course, nor can it affect academic or personal standing in any fashion whatsoever.

There are several benefits to be expected from participation in this study. I expect participating students to be better equipped with skills for laboratory measurement and data collection which will serve them well throughout their high school careers and beyond. Also, as I become more familiar with student strengths and weaknesses, I will better equipped to aid their academic development.

Participation in this study is voluntary, and students are free to withdraw consent and to discontinue participation in this study at any time without prejudice from the investigator.

Please feel free to ask any questions of Mr. Daryl via e-mail at daryl_h@icsbangkok.com, phone, or in person before signing the Informed Consent form and beginning the study, and at any time during the study. If you have additional questions about the rights of human subjects you can contact the Chair of the Institutional Review Board, Mark Quinn, 001-406-994-4707 [mquinn@montana.edu]

AUTHORIZATION: I have read the above and understand the discomforts, inconveniences and risks of this study. I, ____________________________________ *(name of parent or guardian),* related to the subject as _______________________________________ *relationship,* agree to the participation of ____ *(name of subject)* in this research. I understand that the subject or I may later refuse participation in this research and that the subject, through his/her own action or mine, may withdraw from the research at any time. I have received a copy of this consent form for my own records.

Signed (Parent/Guardian): ____

Student Signature: ____

Investigator: ____

Date: ____

APPENDIX H

INSTITUTIONAL REVIEW BOARD EXEMPTION LETTER

Appendix H
Institutional Review Board Exemption Letter

MONTANA STATE UNIVERSITY

INSTITUTIONAL REVIEW BOARD
For the Protection of Human Subjects
FWA 00000165

960 Technology Blvd. Room 127
c/o Veterinary Molecular Biology
Montana State University
Bozeman, MT 59718
Telephone: 406-994-6783
FAX: 406-994-4303
E-mail: cherylj@montana.edu

Chair: Mark Quinn
406-994-4707
mquinn@montana.edu
Administrator:
Cheryl Johnson
406-994-6783
cherylj@montana.edu

MEMORANDUM

TO: Daryl Holst

FROM: Mark Quinn, Ph.D. Chair *Mark Quinn cy*
Institutional Review Board for the Protection of Human Subjects

DATE: November 22, 2010

SUBJECT: *"Inquiring into Measurement Error" [DH112210-EX]*

The above research, described in your submission of November 12, 2010, is exempt from the requirement of review by the Institutional Review Board in accordance with the Code of Federal Regulations, Part 46, section 101. The specific paragraph which applies to your research is:

_X_ (b)(1) Research conducted in established or commonly accepted educational settings, involving normal educational practices such as (i) research on regular and special education instructional strategies, or (ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

___ (b)(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

___ (b)(3) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior that is not exempt under paragraph (b)(2) of this section, if: (i) the human subjects are elected or appointed public officials or candidates for public office; or (ii) federal statute(s) without exception that the confidentiality of the personally identifiable information will be maintained throughout the research and thereafter.

___ (b)(4) Research involving the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, if these sources are publicly available, or if the information is recorded by the investigator in such a manner that the subjects cannot be identified, directly or through identifiers linked to the subjects.

___ (b)(5) Research and demonstration projects, which are conducted by or subject to the approval of department or agency heads, and which are designed to study, evaluate, or otherwise examine: (i) public benefit or service programs; (ii) procedures for obtaining benefits or services under those programs; (iii) possible changes in or alternatives to those programs or procedures; or (iv) possible changes in methods or levels of payment for benefits or services under those programs.

___ (b)(6) Taste and food quality evaluation and consumer acceptance studies, (i) if wholesome foods without additives are consumed, or (ii) if a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the FDA, or approved by the EPA, or the Food Safety and Inspection Service of the USDA.

Although review by the Institutional Review Board is not required for the above research, the Committee will be glad to review it. If you wish a review and committee approval, please submit 3 copies of the usual application form and it will be processed by expedited review.