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Using a Disciplinary Literacy Framework to Teach High School Physics

An Action Research Study

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Introduction

Hurley teaches a high school course called Conceptual Physics. When he asked what the difference was between conceptual and regular physics, he was told, “Math.” In other words, he was to teach physics using concepts rather than math and was armed with Hewitt’s (2006) excellent textbook.

As a former Science Technology Engineering and Mathematics (STEM) professional, Hurley felt that teaching physics without math was somehow lowering expectations. He struggled to teach the material without introducing some mathematics at various points, so he taught math where he thought it was appropriate with mixed results—some units were successful and some were not.

Hurley’s supervisor, recognizing his struggles, suggested he speak with the school’s literacy coach, Henry. He observed Hurley’s classroom for two weeks and offered that he did not have a math cognition problem; he had a literacy problem.

Henry felt, based on his observations, that much of the language and representation of the language with variables was not understood, and that when students understood the language and variables, the math was completed successfully. Most of the math used in a regular physics class is simple algebra with some trigonometry—math classes that most students have already taken or are taking at the same time as physics class. In other words, students were able to do the math, just not in the physics context.

After a year of exploring different options and testing out a few ideas, Henry and Hurley developed an instructional framework that made disciplinary literacy the focus. This action research study conducted over one year was designed to help answer the question: If students are taught physics using a disciplinary literacy framework, would students be able to explain their understanding of physics phenomena using mathematics?

Literature Review

> Through language analysis, teachers can convey to students that the language is a means through which students make meaning of the content within the discipline, thus making the vocabulary of the discipline the most critical component to be learned (Fang & Schleppegrell, 2008).

Hurley's interaction with the literacy coach led him to believe that to learn physics requires being literate in the discipline of physics. Physics demands the use of highly specific language, highly specific actions, and the application of highly specific mathematical functions (i.e., computational thinking). To learn physics, then, students must master the precise language, the particular behaviors and tools, and the practical mathematics of the discipline (Next Generation Science Standards [NGSS, 2013). A breakdown in any one area means a breakdown in the learning of physics. These areas are: (a) the ability to write and speak using physics language and (b) the ability to visualize phenomena in a physicist-like context. The literature review will present literature in each of these areas preceded by connections to *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council, 2012) and the NGSS (2013) Science and Engineering Practices.

Writing and Speaking in a Physics Classroom

Physicists read and write to attain, assess, and deliver information relevant to their research (National Research Council, 2012). They read and write to clarify their investigations and to help them identify problems and solutions (NGSS, 2013). To do so, physicists often chart and summarize readings as they are applicable to their own areas of interest (Shanahan & Shanahan, 2008). Physicists, like other professionals, employ specific literacy strategies to meet their disciplinary professional needs. For physicists, reading and writing are necessary in the aid of the development of their research projects. While reading, writing, and language are important for learning new information and methods, all physicists accept that they spend the majority of their time reading and writing for the purpose of immediate application in their own research (Bazerman, 1985).

Like scientists in the field, students in a physics class should engage in written and oral arguments grounded in evidence and presented with linguistic precision and accuracy (National Research Council, 2012). As physicists do, students should communicate information in multiple ways (e.g., charts, tables, graphs, pictures, writing, and oral presentations) using the linguistic, mathematical, and conceptual modes that are accepted in the field of physics (NGSS, 2013). One way to achieve sound vocabulary learning and use is through disciplinary literacy practices. Disciplinary literacy, as defined by Shanahan and Shanahan (2008), are the "[l]iteracy skills specialized to history, science, mathematics, literature, or other subject matter" (p. 44). Engaging in disciplinary literacy learning includes students not only gaining knowledge of a particular discipline but also participating in and understanding how knowledge is constructed and shared in the discipline (Moje, 2008; Shanahan & Shanahan, 2008). Through a disciplinary literacy approach, teachers can make tangible the language of the discipline and can give students strategies for analyzing the content of the discipline in sophisticated ways (Fang & Schleppegrell, 2010). Through language analysis, teachers can convey to students that the language is a means through which students make meaning of the content within the discipline, thus making the vocabulary of the discipline the most critical component to be learned (Fang & Schleppegrell, 2008). As students work to create explanations or to design solutions as is recommended by the National Research Council (2012), the information must be highly accurate—making the precise meaning of each word and/or clause important. In physics, as in all other sciences, scientists must communicate clearly the ideas and methods they generate (NGSS, 2013). According to the NGSS, in the physics classroom, therefore, students must communicate clearly and accurately in a variety of communicative contexts.

Shanahan and Shanahan (2008) and Moje (2008) recommend that high school teachers use this knowledge to design curricula which help students learn, use, and produce a variety of texts in particular disciplines. To do so in physics, Yore, Pimm, and Tuan (2007) state that teachers can encourage "…purposeful discussion, reading, and writing embedded in authentic inquiry and problem solving that move language from everyday usage to the specialized disciplinary uses [that] can enhance learning for understanding" (p. 565).

High quality science instruction, as delineated in the NGSS (2013), should consist of students participating in language-intensive science discourse on a regular basis. Because every learning situation in science is a language-learning situation, students need to practice deciphering and producing texts similar to those produced in the field (National Research Council, 2012). Like physicists, students should engage in physics-specific literacy practices—reading, writing, and interpreting tables, graphs, diagrams, charts, text, and visuals while conducting authentic scientific work. Recent trends in secondary research and design have scrutinized the literacy practices in secondary schools (International Reading Association, 2010). Secondary schools do not appear to some to be lessening language deficiencies in secondary classes because students are continually graduating without command of sophisticated language (Forrest, 2006). This can be directly attributed to the vocabulary practices offered to older students, which often is scant (Flynt & Brozo, 2008; Lesaux, Kieffer, Faller, & Kelley, 2010). For example, the Carnegie Corporation's (2010) report states that "just pronouncing the words correctly is not enough, since students in middle and high school are often expected to learn the meanings of such words from context alone" (p. 14). While this appears to be stating the obvious, many high school teachers are not teaching vocabulary beyond "pronouncing the word," and if they do, it usually amounts to nothing more than arbitrary definitions and sentences (Bromley, 2007). Teachers are continually using approaches that do not reflect the robust nature of the language used in science (Nagy, 1988). To learn vocabulary so that it is useful for students in a secondary science classroom, then, instruction time needs to be of high quality (Allington & McGill-Frazen, 2004).

Physicists use language and literacy to construct explanations and models and to test hypotheses. They use language and literacy to evaluate competing designs and to test for design flaws (National Research Council, 2012). Students can be required to use literacy in the same capacity in the physics classroom. As such, students can gather, read, and evaluate information from multiple sources and use that information to construct their own explanations, models, and hypotheses regarding the authentic physics tasks in which they are engaged (NGSS, 2013). In order to provide quality vocabulary instruction, teachers should keep the following principles in mind:

1. Words should be prominent in all classes. If not, students become uninterested in words and their meanings (Bromley, 2009).

2. Instruction should address the current content words and should also include components in addition to definitions for future application in future contexts (Nagy, Berninger, & Abbott, 2006).

3. Students should be encouraged to take ownership of their word knowledge (Marzano & Pickering, 2005).

4. Instruction should be stimulating to reach students in a meaningful way (Beck, McKeown, & Kucan, 2002).

5. Instruction should incorporate reading so as to provide authentic tasks for applying and expanding word knowledge (Allen, 1999; Allen, 2007; Beck et al., 2002; Beck, McKeown, & Kucan, 2008; Serafini & Serafini-Youngs, 2006).

Visualization in a Physics Classroom

One additional specialization of disciplinary science literacy is the language of mathematics and how mathematics can describe the world that surrounds students. Students in science classes, perhaps to a greater extent in physics than other science classes, are required to use math extensively. Using a range of mathematical and computational thinking helps students to better understand the phenomena and design appropriate investigations or experiments (NGSS, 2013). In physics, mathematics and computational thinking should be used throughout the entire investigative process. Mathematics should be used to plan, analyze, and interpret phenomena with the purpose of communicating scientific findings that are grounded in data and evidence (National Research Council, 2012). When using models or computational thinking to aid in understanding or interpreting a phenomenon, students struggle with comprehension because they may lack the ability to visualize the phenomenon mathematically (Van der Veen, 2012).

Constructing drawings, diagrams, models, and systems can help students to better understand the possible outcomes of their work, thus making the mathematical application more visible, improving explanatory power and computational thinking (National Research Council, 2012). Like physicists working in the field, students can use diagrams and drawings along with their mathematical representations to explain the phenomena under investigation (NGSS, 2013). Van der Veen (2012) offers that language and mathematics are similar in that once rules of association are understood, new meaning can be derived from successful application of those rules. Further, Van der Veen (2012) suggests that since equations represent complex relationships, and vocabulary and language can also be used to represent complex relationships, the language of the arts can help students see how math equations represent the world around them (p. 364). Van der Veen (2012) is suggesting that drawing or graphically depicting phenomena or concepts in a physics classroom will help students make sense of mathematics' use in physics class.

Pictorial models help students to better understand their findings and to develop stronger explanations (National Research Council, 2012). Because data, findings, and trends are not always as straightforward as people would prefer, physicists use a variety of tools to communicate understanding. Like physicists, students too can use conceptual drawings to help them communicate and question their understandings more precisely (NGSS, 2013). Kendrick and Roswell (2013) also suggest that teachers instruct students to write and draw pictures when making meaning of a concept. When a student writes and draws a picture as a means to explain a concept or idea, Kendrick and Roswell (2013) contend that the student takes ownership of the material and applies knowledge from their own experiences to make new meaning—that the act of drawing and writing about the phenomenon helps students merge their own experiences and prior knowledge with the newly learned concept.

In science classes, students should plan and carry out their own investigations individually and in collaborative groups. In these in investigations, students must include their observations and support them with linguistic, mathematical, and conceptual evidence from a variety of sources as scientists in the field do (National Research Council, 2012). Through their investigations, students can then create meaningful models that represent their understanding of the scientific phenomena under investigation. These models—diagrams, tables, charts, drawings, mathematical representations, analogies, and computer simulations—can then be used to communicate their scientific understanding beyond the simple recall of information. These models can be used to predict, question, and communicate explanations or proposed systems (NGSS, 2013). In physics class, teachers have an opportunity to expand student experiences beyond prior personal experiences by creating a new sensory encounter via experiments. Results from Reiner's (2009) study suggest that students' understanding of a physical system, as in the form of an experiment, is derived from physically interacting with that system. Reiner (2009) also suggests that this physical interaction with the experiment creates an immediate picture in students' minds of the concept or how the experiment functions. This mind picture—sometimes referred to as imagery or visualization—then adds to a student's personal set of experiences which helps to understand the concept.

Presmeg (2006) offers the following definition for mathematical visualization: "Visualization is taken to include processes of constructing and transforming both visual mental imagery and all of the inscriptions of a spatial nature that may be implicated in doing mathematics" (p. 2). Presmeg (2006) suggests that both students and teachers alike use visualization to assist in understanding math, but the exact nature of how an individual visualizes or creates imagery is difficult, if not impossible, to identify. However, researching how students visualize in a math context has provided some key insights into how students learn math and how valuable visualizing math can be for students (Presmeg, 2006). It is not enough to simply do the math or use computations to say that there is understanding. Like professional scientists, students need to construct models that demonstrate that the math, in fact, matches the physical phenomena under investigation. Models that include pictures, labels, and data provide more literal interpretations of the mathematics and computation used to describe the phenomena (National Research Council, 2012). If there is not a match, students can use their understanding of the mathematics and their conceptual drawing to reconcile the disagreement. They can use the visual to revise and reconcile the mathematics, and they can use the mathematics to revise and reconcile the visual model. If there is a match, students can use the mathematics to strengthen their explanations of the physical phenomena and they can use their model to strengthen their explanation of how the mathematical or computational model represents physical phenomena. Using mathematical and conceptual models provides students the opportunity to strengthen their ideas and explanations (NGSS, 2013). Through multimodal analyses, students inductively build their understanding of scientific phenomena and deductively check for divergence or convergence of ideas. Together, students can use their mathematics along with their conceptual drawings and language to analyze their findings and synthesize their communication and arguments.

Throughout school in science classes, students should be required to engage in communication and argumentation around scientific investigations and observations as scientists do in the field. The context of the classroom should reflect authentic scientific contexts where careful descriptions and precise statements are the norms of the classroom (National Research Council, 2012). Using the language, mathematics, and behaviors of scientists, students should ask and refine, with the help of the teacher and their peers, their own questions regarding the class content (NGSS, 2013). Students should be guided in the development of investigations that meet the rigors of scientific work, and they should be required to explain and defend their empirical findings with precision and accuracy, using problem-solving tools accepted by scientists. In Reiner's (2006) research, environmental context is similar to what Kendrick and Roswell (2013) described as prior experiences for their students, except that Reiner's students' experiences were more phenomenological, whereas Kendrick and Roswell's were emotional and sociological in nature. In both studies, students used their past experiences to help make meaning of a situation in a context. Reiner's research suggests that this context is important when attempting to think abstractly or symbolically because the context helps trigger implicit knowledge which then helps students make sense of the abstract or symbolic. Math, in physics, is by nature symbolic—there are many variables that represent physical behaviors as well as quantities to be used in math expressions. If, like the students in Reiner's study, students are exposed to a context that triggers background knowledge, students will be able to make more meaning from symbols or mathematical variables.

According to the National Research Council (2012), students need to be provided with a range of opportunities to learn science in classrooms where students are encouraged to bring their own ideas forward and conduct science that follows the norms for scientific participation. To do so, science classrooms must reflect the knowledge and skill-level of the students while at the same time preparing students to think, talk, construct, and behave as scientists and engineers in the field do (NGSS, 2013). Context triggers can be created by teachers via experiments conducted in a laboratory setting on a weekly to semiweekly basis. As students interact with the experiments, they are creating a reservoir of what Reiner (2006) would refer to as triggers to assist in understanding math expressions that represent behaviors in the laboratory setting that they are observing. These variables in the math expression are derived from physics words and, according to Van der Veen (2012), if students are encouraged to draw and write about these variables, they may be more apt to learn or at least appreciate the mathematical aspects of the phenomenon that those variables represent.

> Science classrooms must reflect the knowledge and skill-level of the students while at the same time preparing students to think, talk, construct, and behave as scientists and engineers in the field do (NGSS, 2013).

Literature Review Conclusion

To understand physics, students need to understand the esoteric language of physics. “Throughout their science education, students are continually introduced to new terms, and the meanings of those terms can be learned only through opportunities to use and apply them in their specific contexts” (National Research Council, 2012, p. 76). To address this, students need to be asked to engage in scientific communication regarding their learning of the content. To engage in the necessary reading, writing, speaking, and listening that is required to participate in a community of science learners, students need to learn and use the language precisely on a regular basis along with the conceptual drawings, models, and mathematics that are used as evidence to support their claims (NGSS, 2013).

Helping students visualize through drawing and remembering past experiences can help students understand the math that underpins physics concepts as well as conduct experiments in a laboratory where students can “see” the physics. As students experiment, they encode physics knowledge, and that physics knowledge can be used when deciphering how to mathematically solve a problem or create a math expression that represents a physical phenomenon experienced in the lab (National Research Council, 2012). If students are able to draw or graphically represent that experience in the lab prior to or at the same time as they attempt to create or solve a math problem, they may be more apt to construct a successful mathematical understanding.

Methodology

Based on the literature review, we determined that we needed to help students be able to: (a) write and speak using physics language, (b) graphically depict phenomena, (c) create and conduct experiments representing phenomena, and (d) translate phenomena into mathematical representations. In order to meet these four aspects of physics literacy, each physics unit needed deliberate instruction in each of these areas. In order to do so, we created an instructional framework which we executed for every unit. Unit length would vary based on the topic, for example, one-dimensional motion is a 2-week unit whereas Newton’s 3 Laws are a 4-week unit. All physics classes in the school are taught the same units in the same order. In this study, 11 units were taught.

Student-Participant Background

Seventeen of the 18 students in the honors physics class that this study examined spoke a language other than English at home and were all in the upper quartile in terms of class rank. All students were 11th graders and were between the ages of 16 and 17. Over 45% of the students at the school qualify for free and reduced lunch. The community this school serves is a collar suburb of a large city and can be described as a diverse working class community. This honors physics class was comprised of seven females and 11 males. Languages that were spoken by students in this class were Tagalog, Romanian, English, Spanish, and Polish.

Disciplinary Literacy Framework

The physics class in this study was taught according to a specific framework. For each new unit, the first day of the unit was an internet-based research day. Based on a prompt from the teacher, students would conduct research about the new unit. Students were expected to take notes in their notebooks. Day two consisted of vocabulary review where students would work in pairs or in groups using various vocabulary strategies developed with the literacy coach focusing on core physics terms. Day three was referred to as the board session day and was reserved for math practice which usually consisted of a worksheet with word problems. Students worked individually on this assignment but were able to choose where they sat and were able to work with peers if they desired. In the beginning of day three, the teacher handed out the worksheet, gave a few minutes for the students to look it over, and then asked for questions. As students asked questions about the worksheet, the teacher worked on the dry erase white board in the front of the classroom where the teacher might do an example problem, answer questions, or ask more questions to elicit physicist thinking. Day four and five—depending on complexity of the unit or student ability—consisted of designing and presenting student experiments. The purpose of these experiments was to empirically demonstrate student understanding of the concepts in the unit and was conducted in assigned groups. Each demonstration had to include measurements and mathematical representation of the phenomena being demonstrated. Students in the audience were encouraged to ask challenging questions of the presenters for extra credit.

Data Analysis and Interpretation

Data was collected throughout an entire school year as part of the teaching process. Qualitatively, lessons and parts of lessons were videotaped and conversations with and amongst students were recorded. Quantitatively, teacher-created summative assessments were analyzed along with common summative assessments created by a test generator with modifications made by a physics teacher committee in the school. The teacher was also formally evaluated four times by two different administrators during the year using a modified version of Illinois' new mandated teacher assessment instrument—the Charlotte Danielson Framework for Teaching Evaluation Instrument (Danielson, 2007). We coded, then analyzed and interpreted the comments from that instrument. At the end of the semester, we conducted a Q-sort focus group interview with students in the class.

First, we will present a critical incident that forced us to alter the framework. We will then present data based on the observations according to the Charlotte Danielson Framework (Danielson, 2007). After presenting the observation data, we will present results of the Q-sort focus group ending up with presenting summative and formative assessment data. As each data is presented, we will also offer our interpretation of that data.

Board Session Critical Incident

During an observation of a board session, where students were given a math-based worksheet and were supposed to ask the teacher questions about the research, the literacy coach observed 17 of 18 students asking 28 questions in 30 minutes. Only two of those questions did not relate to the topic. Such a high number of questions was unexpected because, according to Graesser and Person (1994), students ask, on average, 0.11 questions per hour in school (pg. 105) or about one question every 10 hours.

After we reflected on the quantity and nature of questions asked during this board session, we realized that some of the terms and questions students asked about were neither on the vocabulary relay the day before nor part of the worksheet. We realized that these questions came from students' notes based on Monday's research.

Students, it turned out, had many questions about the research they conducted, but we had constructed the framework to do research during day 1 of the unit, then conduct a vocabulary relay on day 2, and then have a board session day 3. While the vocabulary relay was necessary because those terms were critical to understanding physics, they were not the ones students were using to construct their own knowledge.

In short, we felt the schedule was wrong—the board session day should have been placed after the research day and the vocabulary day after the board session day. Once the order was switched, we were able to see what new terms needed to be placed on the vocabulary relay. By swapping days in the framework, we were better able meet the vocabulary needs of the students because the terms on the relay were the ones students were genuinely interested in knowing.

Another insight, and why this epiphany of switching days is considered a critical incident, was that the classroom became a student-driven classroom during these board sessions. Once the change was made, students began directing how the teacher should behave. For example, the students asked the teacher for a model with which they could visualize rotational motion. State law mandates a specific evaluation framework for teachers and that framework rewards higher scores for classrooms that are student-driven. The more a teacher demonstrates that their classroom is student-centered, the higher the score they will receive based on the mandated framework. Switching days, then, became critical to the teacher as a professional as well.

Upon reflection, the teacher realized that students needed time, immediately after research, to make their learning personal and constructive to themselves, not at the behest of the teacher. This was perhaps best said by Danny J., a student in a video recorded after a board session, who stated that in this class, "you have to learn, before you *learn*." We interpret Danny J.'s statement to mean that in order to recognize what students need to know, students need to first investigate the concept somewhat, and that only after an initial investigation is the student ready to learn this new concept. By switching the board session and vocabulary days, the classroom went from being a variation of Lemke's Triadic Classroom (1990) to a student-centered classroom where the teacher served as students' facilitator—a place where students were able to learn, in Danny J.'s sense of the word.

Administrators' Evaluations

The teacher was evaluated five times over the course of the year. Four of the five evaluations are presented here. One of the five is not presented because it occurred during a statistics class, not physics. State law requires a specific format for evaluating teachers, and administrators must attend 50 hours of training before they can become certified to evaluate teachers using that format. This was the first year teachers in our school were evaluated using the new instrument.

Observing administrators must provide evidence for their ratings, and evidence comes in the form of observation notes. One administrator was the math and science chair who observed three classes, and the other was the assistant principal who observed one class. Both emailed their observations to the teacher and the literacy coach, and the authors of this study compiled all the comments into one document and coded them.

First, comments were separated according to whether they were student behavior-oriented, relating to what students said or did. Other comments were statements like, “Teacher greeted students by the door at the beginning of class,” “There is a clear air of respect between teacher and student,” or “The overall environment of the class was relaxed, but business-like.” Of the 51 total comments made while observers were in the classroom, 35 comments (68% of all comments recorded on the observation) were related to what students were doing or saying that could be categorized as exhibiting scientific behaviors. Observers either directly quoted or provided written descriptions about what students were doing or saying.

Second, we coded the 35 observer comments about what students were doing or saying during the observation period according to four different categories that distinguish scientific behavior: (a) being able to design experiments, (b) being able to write and/or speak scientifically, (c) being able to translate observed behavior or measurements to mathematical expressions, and (d) being able to draw a diagram or model of the observed behavior. Students who are fluent in scientific disciplinary literacy exhibit these behaviors and we wanted to see if the administrators observed the same.

Class procedure comments related to how the class is run on a daily basis—behavior that related to taking notes, getting materials, reading the task of the day, and so forth. Comments about class environment related to how the classroom felt to the observer (e.g., “the atmosphere in the classroom was casual, but business-like”). Instances where the teacher told students what to do were coded as teacher providing direction. When a student misbehaved and the teacher corrected the behavior, that comment was coded as teacher correcting student behavior. Teacher behavior related to comments such as, “The teacher was positioned in the back of the room and was available to answer student questions. He shared the rubric he uses for grading the presentations.”

Sixty-eight percent of all comments recorded by administrators were what students were saying or doing in a scientific way. Conversely, 6% (3/51) of the comments recorded had to do with the teacher providing direction. These data suggest that if one teaches using a disciplinary literacy framework like what was done in this study, the classroom supports a student-driven classroom the way Lemke (1990) describes and Ross and Frey (2009) advocate.

Lee and Smagorinky (2008) contend that the discipline-specific language and behavior recorded by the observers in this study needed to be scaffolded by the teacher. It is no surprise, then, that this data agrees with Lee and Smagorinsky’s (2008) assertion considering the framework was used for every unit throughout the year. Students were exposed to multiple instances of learning and practicing science during every unit gaining the practice and fluency needed to demonstrate scientific behavior.

While an observer can choose to record any conversations or behaviors amongst students and teachers during a 50-minute class session, we believe the fact that 68% of the time the observer chose to record information about students is significant. Students were engaged in scientific behaviors and did not rely on the teacher to provide the knowledge or direction actively constructing their own understanding of the content. If the teacher were directing more in the classroom, one could reason, there would be more than 12% (6/51) of the comments about teacher behavior. This data suggests that a disciplinary literacy framework taught from unit to unit may promote a student-driven classroom.

Q-Sort Focus Group

Fourteen students from the honors physics class were asked to respond to the following question: “When you find you are struggling with a math-based problem in science class, what do you do to do get help? Assume that this is NOT a test situation, but something you would have time to find an answer to.” Each participant had 24 cards with strategies students could use to help them with a math-based problem. First, students were asked to separate the 24 cards into two piles—a pile of strategies they have used or currently use and a pile they have never or rarely used. Students were told to write D1 on the back of the cards in the pile that they rarely or never used and to set those aside. Second, students were asked to separate the remaining cards into 3 separate piles according to strategies that were (1) rarely used, (2) sometimes used, and (3) often used. After the piles were separated, students wrote D2 on the sometimes and rarely used strategies and set those aside. Students then ranked the remaining strategies from 1 through however many cards they had remaining—1 being the most used. Students then wrote the number of ranking on the back of the cards.

Once cards were laid out in order, students were asked to share their number 1 card and then by show of hands, who also had this card. A different student was asked what their number 1 card was and then asked which others had that strategy in their top 5. The purpose of these questions was to start a discussion about how students worked through math struggles in a science class. The entire session lasted approximately 25 minutes.

Twelve students ranked “reread the problem” in their top five strategies which they use to help solve a math-based problem in a science class. Eight students placed “refer back to your notes” and “think about what you already know” in their top five. Seven students placed “talk out the problem with a classmate or group of classmates” in their top five.

To reread the problem is a common literacy strategy, and it is not surprising that students would choose this for their top five strategies. Referring back to notes and thinking about what they already know supports Reiner’s (2006), and Kendrick and Roswell’s (2013) findings that students will use prior knowledge to help understand something new. Talking out a problem with others is a social activity and, given how often group work is used as a teaching strategy in this class, and the work of Vygotsky and Piaget, we find this ranking unsurprising.

Students stated that they prefer to engage in what we consider to be more passive strategies before they engage in active strategies. By passive strategies, we mean that students prefer strategies that do not require making a decision (i.e., deciding what is important and what can be put aside). By active strategies, we mean strategies that require decision making (i.e., choosing to use certain pieces, while choosing to leave others out). When students reread, talk to a classmate, refer to notes, or bring forth prior knowledge—those strategies students noted they prefer first—they do not have to make a decision about essential and nonessential information. On the other hand, drawing, looking for key words, or looking for key numbers requires actively deciding what to include and what to exclude; it requires decision making, which according to these data, students would rather do after the passive strategies.

What students discarded is also informative. All 14 students discarded "creating an experiment that will help answer a problem," an active strategy. Thirteen students discarded both "reading the science textbook" or "reading a math textbook." Twelve students discarded "asking parents" or "going back to a previous lab and setting it up to find an answer." Lastly, 10 students discarded "asking a former math teacher for help."

Similar to strategies that students used, all discarded strategies would require active decision making. For example, to seek information from a textbook or to ask an appropriate question would first require deciding what to look up, what to ask, what information could be left out, and finally, deciding if the information discovered is enough to help.

We also found the discard pile surprising because we used a disciplinary literacy approach to teaching the class, so one might think that students would use textbooks to help find answers, but they did not. "Reading either the math or science textbook" was discarded by all students in either the first or second discard pile. Making this even more surprising was that the teacher allowed open-book and open-note quizzes and tests, and there is a set of textbooks always available in the classroom. A possible interpretation of this is that students do not view the textbook as a viable resource to help solve math-based problems.

Students also did not wish to refer back to a lab or create a new lab. At first, this seemed contradictory to the findings of Kendrick and Roswell (2013) and Reiner (2009)—that the tangible, sensory experiences help build knowledge, so one might reason that students would learn to use these sensory experiences to build knowledge. The critical incident and observation data seem to suggest students do learn and explore mathematical relationships in these experiments and sensory experiences, yet the discard piles suggested they do not use them to help solve problems, or at least they do not consider them to be a part of their problem-solving process.

This apparent contradiction might result from students' resistance to making the decisions necessary to solve problems. This may stem from the focus of some science classes being that there is a correct answer, and finding that answer is the goal, not trying different ideas and learning from them. Also, while the option has always existed in this teacher's classroom, he was never explicit about suggesting students could experiment, so students may not have realized it was an option. Or perhaps, as Presmeg (2006) suggests, we do not precisely know how a student visualizes the world mathematically, so more research is required in order to understand how a student would use an experiment or sensory experience to help solve a math problem, when one is posed.

Assessment Data

All physics classes take the same final exams for each semester which are created by test generation software from Holt and modified by all physics teachers as a team year to year as required. These semester exams account for 20% of students' overall semester grades as mandated by the administration and must address all content instructed during the semester. Since these exams are common across all classes, summative in nature, and relatively high stakes for students, we chose to analyze both final exams in this study.

An aim of this study was to discover how physics students use mathematics, so we wanted to analyze the exams for mathematics content. Each exam question was coded according to whether the question required mathematical computation (i.e., the student had to add, subtract, multiply, or divide in order to obtain the correct answer). We refer to these questions as math-based and all other questions as non-math-based. After coding, 10% (4/40) of the fall final exam questions were math-based and 56% (28/50) of the spring semester final exam questions were math-based.

The physics curriculum at our school is usually more math computation intensive during the fall semester compared to spring semester, so the coding results surprised us. The average score on the fall semester exam was 52.3% and the average score on the spring semester exam was 57.81%. We then tested the difference in scores using the Wilcoxon matched pairs test in SPSS to determine if the difference between the two scores was significant.

Sixteen of 18 students took both the fall and spring final exam. One student was excused from the fall final exam due to an extended medical absence and another student was excused from the spring semester final exam because they were a senior and all seniors were exempt from spring semester final exams. The results of the Wilcoxon matched pairs test for 16 students indicated that the average spring final semester score was significantly higher than the average fall semester final exam score, $z = -2.120$, $p < 0.05$.

Initially, these results were somewhat surprising since students struggled with mathematics and one might have hypothesized that the fall final exam would have had the higher average. Recognizing that the physics teacher did spend two full semesters instructing the class using a disciplinary literacy framework, it is possible that students gained some mathematical skill via disciplinary literacy fluency. However, multiple choice responses do not allow us to analyze the mathematical thinking employed by students because students fill in bubbles without accompanying student work. We needed to know more about student mathematical thinking before we drew a conclusion.

In order to obtain evidence of student mathematical thinking from student work, we analyzed two more summative type assessments: a free-response, teacher-created quiz based on 2-dimensional motion, and an assignment where students created a 3-question momentum and impulse quiz and provided solutions to their own quiz. Each of these assessments was completed after the unit and was designed to be summative in nature. We chose these particular units because they required many mathematical calculations as compared to other units, and each unit was the longest in terms of number of days spent coving the unit in each semester.

First, we assessed a 2-dimensional motion, 4-question free response quiz. Typically, for students in this high school, 2-dimensional motion presents the most significant math obstacle for students. Analyzing 2-D motion requires fluency in trigonometry and involves multiple steps to solve each problem. Anecdotally, conversations with students suggest that physics class and 2-D motion problems are the first time students encounter a single problem that takes so much time and effort to solve. Most students took the entire class period, 50 minutes, to complete this 4-question quiz.

We assessed the quiz using a yes/no format across four criteria per problem:

1. Did the student draw a picture?
2. Did the student list variables?
3. Did the student use a formula?
4. Did the student get the solution correct?

Problems 1 and 3 did not require variable listing, so they were not assessed according to that criteria.

Eighteen students took the 4-question quiz. Two of the four problems provided an opportunity to use three strategies of drawing a picture, listing variables, and writing an equation. Twenty-three instances out of a possible 36 (64%), students chose to use all three strategies resulting in a correct answer 87% of the time. If any two strategies were employed, students obtained the correct answer 68% of the time. Lastly, if students employed one or no strategies, they obtained the correct answer 22% of the time. Seventy-five percent (54/72) of the time, students employed at least two strategies to help solve the problem.

This data suggests that students who use more strategies on a free-response problem have a better chance of obtaining the correct answer. These strategies relate to aspects of disciplinary literacy, so when students employ more strategies, they are demonstrating their fluency in disciplinary behavior, and thus obtain the correct answer more often.

Considering we used a disciplinary literacy approach throughout the year, it is not surprising that students who executed elements of disciplinary literacy performed better on the quizzes. This data supports the findings of Lemke (1990), Moje (2008), Bazerman (1985), Shanahan and Shanahan (2008), and Yore et al. (2007), which suggest that if students behave like scientists, they will perform like scientists, thus increasing the chance that the student will obtain more correct answers on an assessment. Additionally, it goes to reason if students can draw or represent the phenomenon correctly, list the appropriate variables, and provide the equation, they will get the problem correct, which students were able to do 87% of the time. This suggests that disciplinary literacy may help students to perform better when dealing with math-type problems, and thus helps us answer the question asked in this research project.

A key portion of disciplinary literacy not addressed in each of the summative assessments thus far in this paper is that of writing and speaking. The literacy coach suggested that the teacher use a summative assessment where students create the word problems and then solve them so we could evaluate their scientific writing ability. We chose an assessment where students had to create a 3-question quiz and then provide the solutions to the quiz.

We assessed the quiz according to whether three strategies were used correctly: (a) the stem of the question was written correctly, (b) a picture was drawn, and (c) an equation was used. The topics for the unit were momentum and impulse which concluded the second week in February. Momentum and impulse involve math, but no trigonometry or exponential functions. This unit was the second longest of the year, just behind 2-dimensional motion, and the conservation of momentum equation has four terms and potentially six different variables, so we felt this topic would be somewhat comparable in scope and difficulty to the other quiz we analyzed in this paper. All strategies were applicable to all three questions.

When the wording of the question was correct (the question stem), a picture was drawn, and an equation was used, 88% percent obtained the correct solution. When any of the two strategies were used, 68% obtained the correct answer. When one or none of the strategies were used, 25% obtained the correct solution.

These findings were remarkably similar to the free-response 2-dimensional motion quiz, suggesting that students who use more disciplinary literacy strategies score higher on assessments. In order to further isolate the impact of writing, we analyzed when students wrote the stem of the question correctly and then obtained the correct solution. Sixty-one percent (31/51) of the time, students wrote a correct stem and those students obtained a correct answer 58% (18/31) of the time.

Fifty-eight percent, while more than half, is not entirely convincing. We do not believe this data suggests that writing alone is an antecedent for obtaining correct solutions. However, when the correct question stem is accompanied by other disciplinary strategies, this data suggests that students' frequency of correct solutions also increases.

Both summative assessments indicate that students who can employ all available disciplinary literacy strategies get the solution correct the majority of the time. This data also suggests that utilizing more than one strategy also helps improve students' scores.

Discussion

While we, as practitioners, are excited about this data, we also recognize, as researchers, the limitations associated with this study. The sample size is very small, 18, and is also an honors class which typically performs at an academically higher level than regular classes, so it goes to reason that the framework may require modifications if used in classes at other levels. This study is also an action research study in which one of the authors is the teacher of the class and the other author is the literacy coach in the teacher's school. We tried to correct for this bias by including administrator evaluations into this study and analyzing common assessments that were not the sole creation of the author. Latent biases may exist in the coding of the free-response student assessment, so we attempted to correct for this bias by using a teacher-designed and a student-designed assessment while including the literacy coach's interpretation of the results.

In this study, we initially asked if students are taught physics using a disciplinary literacy framework, would students be able to explain their understanding of physics phenomena using mathematics? Fundamentally, the evidence presented in this study suggests that delivering lessons within a disciplinary framework may help students solve math-based problems, so long as students employ disciplinary literacy strategies when problem solving. Data from two free-response quizzes also suggests that students who use disciplinary literacy strategies when problem solving score higher on that assessment.

The role of mathematics in students' learning of physics concepts is still ambiguous, however, and requires further study. While we feel the data presented here supports the assertion that instruction using a disciplinary literacy framework can help improve performance on quizzes, how students relate disciplinary literacy strategies to mathematics is still unclear. Summative final exam assessments possibly support this assertion as well, but more evidence about how students mathematically reason on these multiple choice exams is required.

Even with data suggesting a positive impact of a disciplinary literacy approach, this study did not uncover exactly how students apply different modes of learning toward using math appropriately. When we asked students how they obtain help when encountering math questions during the Q-sort focus group, the analysis of student responses suggests that students seek help passively. Also, students did not want to design a new experiment or conduct an experiment again in order to help solve the math-based problem. Our framework is based on students' active proclivities, so this finding is contrary to what we might expect which indicates further research is required.

While disciplinary literacy strategies appeared to help students score higher on assessments, the exact mechanism of how students visualize mathematics and the orchestration of the four modes of disciplinary literacy in order to make mathematical sense of a phenomenon remains unclear.

Practitioner Implications

Even though we, as researchers, might not understand exactly how students visualize mathematics, using the framework as an instructor has some clear benefits. By structuring how physics was taught (using the framework), the role of the teacher changed from teacher lecturer to student facilitator. This shift from teacher-centric to student-centric classrooms may make meeting the NGSS standards easier considering the eight science and engineering practices focus on student-initiated inquiry (NGSS Lead States, 2013). So in addition to possibly improving student performance on math-based assessments in physics assessments by using a disciplinary literacy instructional framework, the teacher may also be meeting many of the NGSS standards in the process.

Using this framework for a full academic year, the physics teacher, with the literacy coach's help and insights, was able to accurately assess student learning. When using the modes of disciplinary literacy as a tool to assess student work, the teacher knew precisely what students knew and did not know. The teacher was able to design subsequent lessons to address each individual student's needs based on how students performed using each mode (writing/speaking, drawing, translating, or experimenting). These modes also relate well to the eight science and engineering practices in the NGSS, so by assessing these modes, the teacher is also assessing whether aspects of the NGSS have been met.

The physics teacher also learned that in order for a student to know physics, and to verify that a student knew physics, he needed to see evidence of how students communicated that knowledge across all modes of disciplinary literacy, not just from a mathematical solution or results from a multiple choice exam. The teacher's confidence about student gaps in knowledge and how he needed to address those gaps in subsequent lessons grew tremendously as a result of this student evidence.

Assessment confidence was bolstered by the student-centered nature of the disciplinary literacy classroom because the teacher has much more time to observe and interact one on one with students and groups in a meaningful way facilitating accurate assessment. In other words, if students are acting like scientists in the physics classroom, then the teacher has more time to observe, encourage, and assess students instead of lecturing in front of the classroom or spending time delivering lesson instructions.

This study has led us to believe, as practitioners, that focusing on disciplinary literacy in a science classroom, with the consistency that an instructional framework offers, yields insights into student learning of physics that seemed inaccessible via traditional teacher-driven pedagogy.

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