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The Impact of Visual Literacy in Secondary Science Education

Elise M. Miller
Bethel University

THE IMPACT OF VISUAL LITERACY IN SECONDARY SCIENCE EDUCATION

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APPROVED:

Thesis Advisor: Karin Farrington, M.A.

Program Director: Molly Wickham, Ph.D.

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ABSTRACT

Visual literacy, or the ability to make sense of and produce images, is an essential but long underrated skill in science. Career scientists and engineers decode and encode information in pictorial form using visual literacy skills regularly. This research will explore first the purpose of science education in the United States and how its reforms have been influenced by career scientists. It will explore if visual literacy skills are aligned with these purposes. This research will then investigate the benefits of incorporating visual literacy in science education to this end. Finally, this research will outline research-based instructional strategies for integrating visual literacy education alongside the science content and practices emphasized in the current standards.

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CHAPTER I: INTRODUCTION

Visual literacy in science

The modern world is saturated with visual information. Despite this, the skills to critically analyze visual representations from drawings to diagrams are unfortunately not something students learn by exposure to images alone. Those who do know how to read visual information and design their own visual communications are better able to create the mental models essential for success in learning science (Kragten et al., 2013), communicating one's learning, and preparing for college, career, and citizenship. In fact, generating both mental and conceptual models is such an integral practice of science and engineering that it has been identified by the Next Generation Science Standards, or NGSS, as one of only eight core practices integral to STEM fields. Effective use of models common in science and engineering like diagrams and drawings hinge on one's visual literacy, or the ability to interpret visual information into verbal or written language and vice versa. Thus, NGSS-aligned science education must develop students' visual literacy skills so they can effectively develop and use models and gain all the ensuing benefits.

As science educators across the United States seek to implement NGSS or NGSS-inspired standards, instructional implications from the current research about visual literacy must be identified to achieve this goal. These instructional implications should address both increasing students' ability to interpret models as well as create their own models of information. One concern to address is identifying the best sources for visual literacy education among the tremendous breadth of visual materials that may be utilized in classrooms from textbooks to trade books to animations on the internet. Finally, there is a huge range of potential instructional strategies but a limited amount of time with students to teach these skills. The most effective methods should be identified and utilized in visual literacy education.

Definition of terms

Term	Definition
Visual literacy	the ability to understand images and use them to think, learn, and express oneself
Visual representation	any pictorial depiction of a phenomenon or set of data that may or may not include text or be integrated into a print text
Graphical representation	any visual representation that includes elements of a graph or diagram such as axes or arrows
STEM	the disciplinary areas of science, technology, engineering, and mathematics
Model	a sketch, diagram, simulation, 3-dimensional replica, or other tangible representation of a phenomenon
Multimodal media	any media that uses more than one mode to communicate in one work such as a textbook page using both a diagram and print text or video clip using both audio voiceover and animation
Inquiry learning	learning experience characterized by students investigating a question or problem
Encode	to convert one's understanding of a phenomena into a tangible form another person may interact with such as an illustration or written explanation
Decode	to convert an external communication such as print text into an understanding of what is being communicated

THESIS QUESTIONS

In developing visual literacy in students, the following questions are addressed in this thesis.

1) What is the impact of visual literacy skills on students' capacity to learn and succeed in life?

2) How does visual literacy connect with the historical context of science education?

3) What are the most effective instructional strategies for visual literacy in secondary science students?

4) What effect does the practice of developing models have on students’ ability to interpret models?

CHAPTER II: LITERATURE REVIEW

Research Inquiries Used

Materials utilized in creating this thesis were found through the Bethel Library and ERIC. Items were found by using search terms "science visual literacy," "graphical literacy in science," "diagrammatic literacy in science," "visual literacy assessment," "visual literacy instruction," "visual literacy secondary education," "visual literacy in the workforce," "history of science education," and "trade books in science." While resources covering history have been selected from a wide range of years to provide more authentic perspectives on science education over time, most research on the impact and effective instruction of visual literacy was published in the last twenty years.

Historical Purpose and Reforms of Secondary Science Education

To understand both the importance of visual literacy in science inquiry and current recommendations in secondary school science education, one must understand patterns of public science education reforms in the United States in these areas historically. These historical patterns repeatedly show a desire for science education that develops thinking over rote memorization with varying degrees of success depending on subject and time period. This aim is also shared by the Next Generation Science Standards (National Research Council [NRC], 2012), the current direction of science education which is based on the National Research Council's Framework .

Presently, the NGSS represents the standards for science in most of the United States: 20 states and the District of Columbia have adopted them as written and 24 states have developed their own standards based on them (NRC, 2012). NGSS emphasizes three disciplines: life science, physical science, and earth and space science. Since these disciplinary areas represent the current focus of science education, the history of each will be explored. Each of the following histories begins in the late 1800’s when science education was transitioning from college preparation for the wealthy few to practical applications for the many citizens living in an increasingly industrialized society. This push for practicality was spurred by World War I, the influenza pandemic, the Great Depression and World War II and persisted until the 1950’s (Chiappetta, 2007). During this time public school attendance grew nationwide and the separate elementary school and secondary school organization was popularized. While each of the three disciplinary areas experienced smaller pushes for reform during this period, it was not until the 1960’s when a “golden era of science curriculum reform” sparked. The launch of Soviet Sputnik and the growth of cognitive science in the 1960’s and 1970’s resulted in both greater interest in science education and greater funding to fuel this golden era. Despite this, student interest and achievement in sciences declined until the 1980’s. At this point, national fear of losing out to Japan and Germany as economic superpowers resulted in another wave of interest in reforming science education (Chiappetta, 2007). Across all reform movements in U.S. secondary science education, the common desire across all reforms has been to facilitate education in a way that makes it more immediately practical in the current cultural and economic moment (Yager, 2000). Despite this, the histories of each disciplinary area are nuanced and best explored separately.

The concept of life science, or biology, being taught as one discipline originated near the end of the 1800's with a push to integrate botany, zoology, and human physiology into one course. It is the only of the three NGSS disciplinary areas that has remained one subject in secondary schools since popularization. Popularity of this integration of subjects at the secondary school level was demonstrated by the growth of general biology as a high school offering. In 1881 only one high school in the nation offered the course, but by 1923 nearly 84% of high schools in the U.S. offered it. While critics were concerned about the loss of rigor by the combination of the three related fields, proponents suggested it whittled the separate disciplines to their essentials so students would spend less time in rote memorization and more time developing conceptual understanding of the similarities across all organisms. Success of "biology" as its own course was further credited to the popularity of general biology at the college level trickling down, a push against the highly technical and academic nature of the three separate fields, and the belief that the less rigorous nature of the integrated field would make the course more accessible and useful to the increasing number of non-college bound students in U.S. public schools illustrating the importance of college and career preparedness in science education across recent history.

While biology education has been justified and promoted in many ways throughout history, Rosenthal (1990) identified all reasoning falling into one of four areas: knowledge, method, personal, or social. Early efforts in life science education through the 1950's emphasized knowledge, although even early on detractors argued this left students full of facts and empty of critical thinking skills. Reformers in the 1960's emphasized the processes of science, similar to what is now commonly called science as inquiry. This aligned with the method reasoning for biology education. In the 1980's and 1990's, the personal and social reasoning for biology took center stage as career education, cultural awareness, personal health, and interests and hobbies were emphasized in science education reforms. The most recent reforms resulting in NGSS align most closely with the method and social reasoning as it seeks to prepare learners to solve problems in their own community and develop their science and engineering practices. This mirrors historical pushes by scientists upon education to develop in secondary students an understanding of common concepts that apply to all organisms, as in the origin of general biology education as one discipline, and the emphasis on scientific practices which has been called for throughout the history of public life science education.

Physical science, unlike life science, is more commonly identified as two distinct subject areas: physics and chemistry. Metzler and Otero (2015) tracked the detailed record of physics' history in public secondary education. One key element they identified is the high involvement of practicing scientists in physics education reform as compared to other disciplines. Formal physics education has followed a similar timeline as biology education. In the late 1800's a movement towards the "inductive method" of learning, similar to modern inquiry-based learning, was popularized among physicists and teachers alike. This spurred an increase in laboratory based instruction at the secondary level. However, in most schools laboratory-based instruction began and remained rote as students were following prescribed directions over and over. Thus, the intention of inquiry-style learning has long been present in physics but without strong execution. Recognition of this failure to generate authentic inquiry "inductive method" learning in the classroom prompted at least two reactionary reform movements between 1900 and 1915, neither successfully producing physics curriculum with more authentic laboratory work.

In following years, tension arising from warring aims of physical science education divided those with vested interest. Physicists argued the aim should be preparing students for college physics education while many educators argued the aim should be preparing students for life in an increasingly industrialized society as other disciplines did at the secondary level. Educators tended to focus on the conceptual elements of physics and how they applied to industrial society and physicists' interest in secondary education dwindled. This continued until the 1950's when the launch of Soviet satellite "Sputnik" resulted in a dramatic increase in funding and interest in science education at a national level, particularly in physical sciences. This resulted in physicists, previously skeptical of public physics education, to re-engage in educational reform. Physics education of the late 1950's and 1960's was marked by a significant increase in mathematical rigor and a slight increase in cultural and technological applications. In the 1970's, physics education research became a formalized field of its own and led to an increase in interest in science education at the elementary and middle school level which had previously been overlooked.

The next shift in physics education in the 1990’s was a return to conceptual physics emphasizing qualitative problem solving over quantitative problem solving and the increase in "physics first" education to give students a conceptual foundation for learning other sciences. This emphasis on conceptual physics and “physics first” programs persists today. One recurring complaint unique to physics education, perhaps due to the long history of formalized physics-specific education research, is that science educators are trained in general science instruction methods and not specifically for physics instruction. The call on physical science educators by physicists is to increase use of scientific practices in the classroom and align instruction more closely with current research on student learning (Metzler & Otero, 2015). In retrospect, the cross-cutting concepts and attention to inquiry of NGSS standards mirrors previous reforms in physics education perhaps aligned more closely to the educators’ bias than the physicists’.

Chemistry is the second discipline that falls under physical science according to NGSS. It is yet another field where historians, scientists, and educators alike have noted similar recommendations for reform made time and time again. Reform recommendations in chemistry since at least the 1920's recognize the U.S. economy is largely driven by science and technology and students need the education to both live and work in this economy, not unlike other disciplines. Also similar to other disciplines, these reforms have seldom been utilized effectively (Lagowski, 1988).

As chemistry spread in public high schools at the end of the 1800's and start of the 1900's, it was often reduced to rote memorization of gas laws, definitions, and a few specific reactions with industrial applications. Much like biology and physics, some scientists and educators did push in the time period between the spread of chemistry in public schools and the 1960's for a movement away from rote memorization and towards more authentic science experience in practice and thought. Unlike physics, there is little record that any of these thinkers were able to organize any widespread reform movements prior to the 1960's, perhaps due to the smaller involvement of career chemists in education as compared to physics. There was an introduction of laboratory work early in the spread of chemistry nationwide but it suffered the same inauthentic rote following of directions that plagued physics. The post-Sputnik age of the 1960's led to, as in other disciplines, more funding and an organized movement towards student learning of general concepts instead of rote memorization of individual reactions. While educators felt this change alone would make chemistry more engaging to students, one chemistry educator of the time remarked retrospectively, "few [educators] knew enough about how young people learn to avoid the pitfalls of being carried away by mature enthusiasms" (Johnstone, 1993). The excitement of educators with these changes would not overcome the difficulties of the highly symbolic nature of learning chemistry, especially without careful application of the cognitive science of learning. Following this period, more formalized chemistry education research began to occur that did begin to address that concern. Like other disciplines, chemistry education researchers lament that there has not been widespread implementation of research-supported practices and instructional strategies for the specific demands of chemistry (Gabel, 1999). The call on chemistry educators is to better equip students to navigate the three multiple representations of matter heavily used - macro, submicro, and representational. Chemistry education may be the area where educators and scientists alike have longest recognized the value of visual literacy skills in science because of its highly symbolic nature.

The final disciplinary area included in NGSS is that of earth and space science. The path of earth and space science, historically viewed as geology and astronomy, is the most historically unique disciplinary area in the current U.S. education system. Unlike the life and physical sciences which grew in popularity and mandate in secondary schools throughout the early 1900's, earth and space science classes started out as being widespread at the end of the 18th century but quickly diminished into a low-enrollment elective in most schools by 1910. This is perhaps because the physical and life sciences were viewed as developing student problem-solving skills in a way earth and space sciences did not. Though scientists and critics of science education across disciplines generally felt science education between the late 1800's and 1950's was not set up to develop strong scientific thinkers, it was perceived that life and physical sciences did this better. Additionally, earth and space sciences were viewed as a derivative of physics itself, and thus less crucial than general principles of physics emphasized at this time.

Even in the early 1960's post-Sputnik era of science education when other sciences saw a boom in funding and interest from academics in improving, earth and space sciences did not increase as dramatically because they were still not viewed as a field that emphasized the processes of science. It was not until the late 1960's and 1970's that earth and space sciences received more attention in education and began to replace physical geography and general science classes that had replaced them in the first half of the century (Dodick & Orion, 2003). However, this increase in earth and space science offerings in public schools tapered off in the 1980's and it remained less common than physical sciences and life sciences as a requirement or even an option. This was partly due to the rise of "physics first" science curricula where 9th grade conceptual physics classes frequently replaced what had been 9th grade earth and space science classes. All told, there was roughly an 11% decrease in earth and space science enrollment in public high schools between 1962 and 2002 despite the uptick of interest in the 1970’s.

Current reflections on the status of earth and space science note that there is a paucity of science teachers with an earth and space science background to teach and advocate for geosciences in schools. Further, there is even a paucity of science teachers who truly employ inquiry based learning in their classrooms which earth and space scientists identify as necessary to authentic earth and space science education (Lewis, 2008). Another element worth noting is that throughout all these descriptions of earth and space science education in the United States, the curricula were not identical. Often, schools would focus on only the geology and astronomy elements in varying degrees, frequently leaving meteorology and oceanography out entirely. As a result, some states or regions had stronger earth and space science education than is generally observed in the national history described. However, overall the earth and space sciences have been less emphasized in the history of U.S. secondary science education.

A common thread among all disciplinary areas is a push across the sciences for inquiry based learning rather than rote memorization. The dream of John Dewey, an early contributor to formal education reform, defined inquiry learning: experiential learning and solving problems relevant to both the learner and society. It was not until the 1960’s that inquiry learning began to be formally backed by formal research. Learning psychologist David Ausbel found that students quickly forgot information learned by rote, backing up what educators and scientists alike had found of science education for decades. Jerome Bruner believed in learning by discovery, an intense form of inquiry learning, and found that this promoted memory of the content and helped learners shift from extrinsic to intrinsic rewards when learning. Famous developmental psychologist Jean Piaget found that learners developed thinking skills, exactly what scientists wanted secondary education to produce, when they were challenged to figure out puzzling events and their tasks were appropriate to their developmental level. The timing of all three researcher's findings, among others, contributed to the boom in science education reform of the 1960's and 1970's described earlier. In addition to these major contributors of the 1960's, cognitive science research since then has continued to support the idea that students learn best when they investigate phenomena in an inquiry context that is familiar in their community (Chiappetta, 2007). Despite the mounting evidence to back inquiry learning, detractors argued the focus on developing thinking skills through discovery would result in a major loss of content they felt was essential for citizens to have.

The NGSS standards appear to be designed to address the concerns and hopes of scientists, educators, and cognitive psychologists alike for education. Each standard addresses cross-cutting concepts found in all sciences, science and engineering practices best suited to use in inquiry, and disciplinary core ideas. Adherence to the NGSS or NGSS-inspired standards in schools moving forward may help to address concerns by increasing use of scientific practices in inquiry learning without loss of the most essential content. Additionally, it addresses some concerns unique to some disciplinary areas. In physics, it puts heavy emphasis on practices of science and better reflects current cognitive science knowledge. Chemistry requires an ability to move between representations of the natural world at different levels with model making which is one of the eight NGSS science and engineering practices. The emphasis on earth and space sciences communicate how essential geoscience is in understanding the many large-scale systems of the natural world as well as contextualizing the time scale of natural inorganic phenomena. Perhaps the national scale of the NGSS standards and how closely they reflect the insights of scientists, educators, and cognitive researchers will allow this generation of reform to affect learners more widely and deeply.

Throughout the history of United States secondary science education reform through the present NGSS standards two things are clear: public education is geared to equip students for their economic futures and students develop thinking skills better through inquiry learning than rote. Weaving visual literacy education into the current science education framework serves both these purposes. Firstly, the overarching direction of secondary science education in the United States has always been to equip students to rise to the economic needs of the era. Now more than ever students will need to navigate an economy filled with visual communication both as an employee and a consumer. The business and consumer worlds are saturated with graphs, diagrams, and other visual representations in the instruction manuals, finance reports, warning labels, etc. that students will need to navigate to find professional and financial success (Brumberger, 2007). Decoding multimodal media like these is an essential skill in science as well and it follows that developing those visual skills serves as a key way to prepare all students for the economic future. Secondly, to be able to fully engage in inquiry practices to develop key thinking skills students must be able to understand myriad multimodal representations used in science. While inquiry learning is often equated with “hands-on” laboratory experiences in science class, it also involves collecting information on what they are exploring from a variety of information sources and communicating their learning (Sotáková et al., 2020) For a student to collect information from science sources involves heavy visual literacy skills as science materials are rife with graphs, diagrams, microscopic photos, tables, charts, artist renderings of methodology, and more. To be able to communicate their learning, both from hands-on experiences and research from other sources, they will be called upon to make models of their learning, heavily emphasized in NGSS, which often involves graph, diagram, or other visual representation creation. Without the ability to decode and encode visual information, students are not equipped to practice inquiry and gain the knowledge and skills that follow. Johnstone (1993 p. 704) acknowledged that learners are tasked "to switch rapidly around [science concepts] to link macrophenomena with submicro and with symbolism" and further stated that doing such without adequate support in visual literacy skills "is to ask for overload of working memory." Clearly, to embrace and execute the recommendations of career scientists, cognitive psychologists, and experienced educators for providing learners with a quality education, teachers must teach their students visual literacy skills.

All three disciplinary areas share a historical record of reformers aiming to reduce the emphasis on knowledge for knowledge's sake and increase the emphasis on scientific practices and the personal and social connections of science through inquiry. Looking at early writings on education revealed a desire for the same improvements desired now. A criticism of science education by Pearson in 1891 could easily describe current science educational reform sentiments of today in saying that, ". . . the pupil is filled with information in regard to science … only in a few exceptional schools is he . . . taught to think for himself" (Rosenthal, 2020, p. 153).

History indicates this pursuit of developing learners who have key thinking skills that will continue to serve them throughout life is supported by many stakeholders of science education.

Impact of Visual Literacy in Science Education

The complexity of visual perception is underappreciated. Light hits the eye triggering electrical impulses to travel through the most powerful information conduit to the brain wherein the brain must quickly filter information, compare that information to prior knowledge, and respond (Burmark, 2008). This process occurs over and over again with the many visual media we experience every day. We rely on this process more and more heavily in an increasingly visual world. As Burmark (2008, p. 5) puts it, “ because of television, advertising, and the Internet, the primary literacy of the twenty-first century is visual”. Critically and effectively engaging with what we see is complex to say the least.

Visual literacy may be defined as the ability to understand images and use them to think, learn, and express oneself. Images falling under this definition include but are not limited to photographs, diagrams, tables, charts, and artistic renderings like drawings, paintings, or digital art. Visual representations like these are becoming increasingly common in uses from academic to professional to social media and more (Dallow, 2007). Visual representations are one form of multimodal media, or media that uses more than one form of expression such as containing both text and images. Navigating multimodal media can be cognitively taxing and often require visual literacy skills that must be taught to students (Arneson & Offerdahl, 2018).

Students enter elementary school with a foundation of visual literacy skills that rivals their print literacy skills. However, because these are not developed as diligently, they do not progress at the same rate (Brumberger, 2007). The results from the intention to focus on developing print literacy which is indeed imperative, but still comes at the cost of visual literacy (Serafini, 2015). Thus, students' visual literacy skills atrophy before they even reach secondary schools, much less college. This can affect students' ability to thrive in science education because there are many abstract science concepts that are best represented visually (Fernández-Fontecha et al., 2019). Attention to visual literacy must be taken seriously early in the secondary level science so that students are equipped for secondary learning and assessment as well as college, career, and citizenship.

Impact on Learning

Visual literacy is essential to a students' ability to learn in secondary science because they aid in promoting learning skills and navigating increasingly visual learning materials. The two primary cognitive theories visual literacy academics source when discussing the learning benefits of visual literacy are the cognitive theory of multimedia learning and the cognitive load theory (Arneson & Offerdahl, 2018). Cognitive theory of multimedia learning as interpreted by Arneson and Offerdahl (2018) indicated that concepts presented with images in addition to text allows for processing a larger amount of information at one time. In contrast, cognitive load theory would suggest that the inclusion of images in texts provided to students could actually raise the cognitive demands of the text by overloading students with information. Arneson and Offerdahl proposed that to reduce this cognitive demand and prepare students better for the demands of multi-modal literacy requires visual literacy skill practice. To help students access the processing power of visual representations they must already be equipped with skills to navigate them.

These skills serve more than interpreting visuals alone. Though visual literacy skills are passed over for print and mathematical literacy skills in school, visual literacy skills actually help enhance both critical thinking skills as well as verbal and written communication abilities. (Brumberger, 2007; Bintz, 2016). Therefore, their inclusion will not hamper students' abilities and education in other forms of literacy but will actually provide a more rounded literacy education for all coursework. Additionally, diagrammatic literacy, a facet of visual literacy, can help students learn abstract science concepts more effectively than text. Diagrams help students build mental models of concepts, improve self-explanation, reduce comprehension errors, and more concrete understandings of abstract ideas by activating their spatial skills (Kragten et al., 2013; Roberts et al., 2014). The ability to create mental models of processes, facilitated by visual representation, is essential in "fostering conceptual change and meaningful learning in students" according to the drawing-to-learn framework developed by Quillin and Thomas (2015, p. 2). This is because it enables learners to generate predictions and explanations from visual sources in addition to verbal sources. Using visuals alongside text increases comprehension as verbal and visual information are processed in different parts of the brain (Burmark, 2008). In fact, students appear to learn more by combining verbal and visual information in practice than verbal information alone regardless of their preferred learning mode (Quillin & Thomas, 2015). Despite the many benefits of multimodal media, many students struggle to decode diagrams and other visual representations used in science indicating a need to develop visual literacy skills.

Part of the issue may be that many students do not realize how powerful graphics in their learning material are. Research by Mctigue and Flowers (2011) indicated that the most prevalent viewpoint among students on purpose of graphics expressed by students was that they were meant to be only a visual representation of the information in the text. Hannus and Hyona (1999) found that students only look at illustrations minimally when reading informational text. Fingeret (2012) conducted a study of science and social studies textbooks, leveled readers, and trade books finding that 58% of the graphics therein contained information not present in the written text. To rely on print literacy alone would leave a student reading informational texts including graphics to miss key information. Students in the McTigue and Flowers study (2011) also expressed they had no strategies for examining diagrams they did not understand other than asking the teacher. McTigue and Flower concluded that reading diagrams must be explicitly taught with an emphasis on both the purpose and conventions of diagrams given that learning materials are increasingly characterized by large amounts of visually-presented information.

The increase in visual information in learning materials can be seen not only in textbooks but also in trade books. Trade books have been used increasingly in classrooms, perhaps because as Coleman and Dantzler (2016, p. 27) explained, they make "science content more meaningful, more relevant, and more updated than science textbooks “As a result, they can be used as a powerful learning tool. However, utilizing these books also requires strong visual literacy skills. Coleman and Dantzler (2016) examined 2067 science trade books recommended by the National Science Teacher's Association between 1972 and 2007 and found that the presence of graphical representations in trade books is increasing exponentially each year. This illustrates both that students will be increasingly faced with graphical representations and that to take fullest advantage of trade books specifically as a learning tool requires strong visual literacy.

Finally, research by Hannus and Hyona (1999) investigated the effect of illustrations in text between high-ability and low-ability children. They hypothesized that because successfully comprehending an illustrated science passage is cognitively demanding, high-ability students will comprehend illustrated science passages better demonstrating better utilization of the illustrations. This is aligned with the cognitive load theory perspective. They asked 108 4th grade Finnish students to recall factual and comprehension questions following the reading of illustrated and non-illustrated texts. Low-ability students performed similar questions for both versions of the text (illustrated and text-alone) while high-ability students outperformed low-ability students on both versions. Additionally, high-ability students scored significantly better on both detailed questions and comprehension questions for the illustrated version of the text when compared to the non-illustrated version indicating that they were able to utilize visual representations for learning better. The authors concluded that this demonstrated that the ability to learn from a text was greater in high-ability children indicating it is a task demonstrating intellectual achievement. It is suggested that low-achieving children lack the decoding ability to integrate text information with visual information provided on learning material and assessment items. The frequently referenced work of Hannus and Hyona (1999) in visual literacy research to the present day demonstrates both that visual literacy is a taxing task where higher-ability students have an advantage, which aligns with cognitive load theory, and that illustrations are a useful aid in comprehension, which aligns with the cognitive theory of multimedia learning. Any teacher who takes the call to teach all students to their highest potential must conscientiously develop visual literacy skills in all students so that all students, regardless of tested cognitive ability or previous experience with visual literacy, can thrive in science.

Impact on assessment

Not only can visual literacy aid students in critical thinking and comprehension, but it can also enable them to demonstrate that on assessments with greater proficiency. The demands of visual literacy in assessment require a student to “learn to ‘read’ (consume/interpret) images and ‘write’ (produce/use) visually rich communication” and “execute these actions with a demonstration of content knowledge” (Burmark, 2008, p. 5). This is true of both standardized tests required by states and college admissions processes but also of the authentic assessments teachers employ in the classroom.

Not only are graphical representations increasingly common in the learning material students are provided, they are also increasingly common on high-stakes assessments that can affect their futures including the ACT, PISA, and state accountability exams (Lamb et al., 2014). College entrance exams like the ACT are particularly imperative for students as this can affect both their acceptance into institutions of higher education as well as scholarship opportunities. Yeh and McTigue (2009) investigated the frequency and type of diagrammatic representations in state standardized tests. This research was spurred by the concern that standardized science tests assess diagrammatic literacy in addition to science content knowledge. In middle school state standardized tests, 46% of assessment items included graphics. Of the nearly half of items with graphics, the two most frequently used graphics were pictorial illustrations (46.3%) and charts and graphs (38.3%). These charts and graphs regularly contained all information required to answer a question. Of all 519 items with graphics in both the elementary and middle school standardized tests reviewed, 54.7% of the graphics contained partial information to answer the question and 28.5% contained all necessary information to answer the question. Diagrammatic literacy, a core component of science visual literacy, is essential to success on standardized tests given the high proportion of questions that contain visuals that had partial or all information necessary to answering the question. While there is no present data indicating that the ACT, PISA, etc. also test for diagrammatic or visual literacy, it is reasonable to assume it is a realistic possibility. If students are not equipped with visual literacy skills, they likely cannot be expected to perform adequately on any form of standardized testing.

Additionally, educators in the classroom often assess student learning, both formatively and summatively, in ways that require visual literacy. Students are increasingly asked to create visual representations such as infographics and slideshows to show their learning (Silverman & Piedmont, 2016). Further in science specifically there are lab reports that require graphs to be made and data and processes to be diagrammed. To enable students to thrive in all assessment settings, they need visual literacy skills to show their learning in authentic assessment tasks like these.

Impact on college success

For many students, college is the next step after secondary education. The demands for visual literacy remain in learning and assessment here across fields. Barbara Stafford (1996) argued that because visualization of knowledge is essential to all professional activities, it is imperative in college curricula. She predicted that increasing use and expectation of visualization in academia affects not only the method of academics but also the theory. All forms of education, from life and physical sciences to humanities, are affected by this shift.

Though the demand for it is present, students cannot expect to be provided with adequate visual literacy education at college. Brumberger (2007) identified little coursework in undergraduate or graduate programs to teach visual literacy necessary to each unique field yet it was a universally necessary skill for learning and communicating information. Further, it was found that not even a full semester of a biology course designed to develop visual literacy was sufficient for developing visually literate science students (Arneson & Offerdahl, 2018). The need for visual literacy is more dire at the college level as the prevalence of graphics is increasing here too. Zacks et al. (2002) found that between 1985 and 1994 the average number of graphs present in scientific journals almost doubled. In summary, students will increasingly need visual literacy skills to be successful in college but cannot expect to receive them at college. Hence, visual literacy skills should be extensively taught and used in secondary education.

Impact on career

Regardless of whether or not they attend university, all students will benefit from visual literacy in their careers. First, it can actually give students an edge in obtaining a job. This is because their competition may share the same writing and reading skill, but will likely not have the same visual communication skills unless they too have been explicitly taught them (Silverman & Piedmont, 2016). Once a student has a position, they will find their visual skills continue to benefit them. Brumberger (2007) purported that visual literacy education also supports the development of creative thinking. This supports learners in their future careers by endowing them with creative expression and problem-solving skills requisite of many careers.

Additionally, visual literacy has been associated with leadership skills in the workplace. Bintz (2016) described this relationship in her qualitative research interviewing corporate leaders and academic leaders in visual literacy. Leadership needs are varied and dynamic but generally require a person to develop critical thinking skills that allow them to respond to situations with reflection and self-awareness. With visual literacy skills, a person is able to understand and interpret visual information and communicate that information with their own analysis back to others, potentially in a visual format. Leaders must also be able to create and communicate a vision. Visual literacy aids in the communication of a vision to a team, company, or consumer by giving a person the skills to design visual materials that evoke the desired thoughts and attitudes. Thus, visual literacy supports skills identified by current leadership theory as necessary to effective leadership in the workplace (Bintz, 2016).

Should students pursue a career specifically in science or engineering, science communication is a core competency they must possess (Arneson & Offerdahl, 2018). Science communication entails the communication of information both among scientists and between scientists and the general public. In science, visual literacy is imperative in communicating phenomena that are difficult to observe either because of scale, whether that is microscopic or global, or rarity. In engineering, visual literacy is imperative in communicating the mechanics of a proposed solution and communicating specifications. In both fields, visual representations are powerful because they can deliver a huge amount of information in a relatively small space. Additionally, as digital technologies progress, the methods in which scientists and engineers communicate are widespread from graphs to computer models to chemical formulae (Arneson & Offerdahl, 2018). To meet these ever changing communication demands in science and engineering, students must have a well developed set of visual literacy skills to navigate the myriad multimodal media in their field.

Both in the sense of providing work that is meaningful to the public and scientific community and in seeking funding for future research, the success of a scientist relies on their ability to communicate effectively (Arneson & Offerdahl, 2018). Because secondary science education is in the midst of a push for education in authentic science and engineering practices, it cannot be complete without "explicitly targeting communication skills that are translatable across multiple disciplines" like "visual representations, [which] as described earlier, are an essential aspect of scientific communications" (Arneson & Offerdahl, 2018, p. 1).

Impact of citizenship

Government agencies and news outlets alike communicate a huge amount of multimodal media to the public. These bulletins can come in the form of safety warnings, health advisories, ecological impact reports, and more. For students to function as engaged, healthy citizens in their communities they must be able to "understand and be critical of information presented in graphical form" (Lamb et al., 2014, p. 25). Being able to understand visual information is a key skill for person health decision making as well as developing opinions on public policy matters (Harsh et al., 2019)

The highly visualized nature of science communication places visual literacy demands on all persons involved in communication, including the general public (Arneson & Offerdahl, 2018; Trumbo, 1999). The unique demands of visual literacy can challenge even those with strong print literacy and education. Traditional text-driven science literacy among adults correlates with education and age but this trend does not exist for visual literacy as studied in Bucchi and Saracino (2016). Historically students have not been equipped for the visual demands of science communication between scientists and the public but must be to engage with multimodal statements.

Even when not seeking current event information, students are exposed to "Instagram activism" in their free time through posts on social media featuring, "design choices intended to pause a user’s scroll and prompt them to read the text" (Nguyen, 2020). The necessity for students to learn how to navigate these multimodal posts is two-fold: students must be able to make decisions regarding both the information in the context of its credibility and students may choose to engage in "Instagram activism" as citizens to spread awareness about causes they desire to promote. If they do choose to engage in creating and spreading their own infographic or slideshow style posts popular on Instagram, they must be able to make strong design choices that draw the eye in an environment of other well-crafted visual information.

Finally, visual literacy can contribute to character education. It was observed by several persons interviewed in the Bintz (2016) leadership and visual literacy study that visual literacy gives a person the ability to see the world through another's eyes when consuming visual media produced by that person. As a result, it is felt that visual literacy education builds emotional intelligence and empathy in students.

Impact on students pursuing science or engineering careers

Silverman and Piedmont (2016) noted that expectations for visual literacy exist in all coursework including science but explicit instruction of visual practices is usually limited to arts and humanities classes. However, the visual demands in science are no less important. In science, there are myriad concepts so abstract that they are best represented visually (Fernández-Fontecha, 2019). This is because scientists must understand phenomena that are either too large, like the cooperative movement of a solar system, or too small, like a chemical reaction, to view directly (Offerdahl et al., 2017). Further, creating visual representations of information is an expectation of practicing scientists (Quillin & Thomas, 2015). This is partly because science is a highly collaborative field where shared understandings of phenomena must be communicated across distance, language, and culture to other scientists (Offerdahl et al., 2017). From interpretation of data presented in tables and graphs to creation of diagrams and models, science students need visual literacy skills to be successful in and out of the classroom.

Science education is also an appropriate place to build visual literacy skills, particularly those of composition, because both design and science are non-linear processes. The current standards for science in much of the country emphasize eight science and engineering skills that are used across a multitude of science and engineering fields (NRC, 2012). The practices are as follows: asking questions (for science) and defining problems (for engineering), developing and using models, planning and carrying out investigations, analyzing and interpreting data, using math and computational thinking, constructing an explanation (for science) and designing a solution (for engineering), engaging in an argument stemming from evidence, and obtaining, evaluating, and communicating information. While some educators, particularly those in lower grades, may still teach these skills as occurring in a linear fashion called "the scientific method", true inquiry involves using these eight skills of science and engineering in different orders that reflects the unique challenges of each area of research or development (NRC, 2012). Visual design, similarly, has key skills like idea generation and development and drafting that defy a linear order but are used throughout a process of creation to communicate. Brumberger stated that, much like science, "design concepts are developed through a process—one whose steps may not be neatly ordered, or even consciously imagined, but exist just the same" (Brumberger, 2007, p. 385) These words are echoed in the framework that resulted in the current secondary science standards, "practicing scientists employ a broad spectrum of methods" and that focusing on the individual practices, instead of one linear method, aids in "[avoiding] the mistaken impression that there is one distinctive approach common to all science" (NRC, 2012, p. 44). If teachers are communicating this effectively, students are primed to understand other non-linear processes. As a result, the science classroom is an appropriate and powerful setting to teach the non-linear practices of visual literacy.

Often, the practices of teaching visual literacy also align with specific practices of science in other ways. Teaching students how to critically read multimodal science news texts and investigating the credibility of multimodal science information material is an ideal example of practice of "obtaining, evaluating, and communicating information" (Lamb et al., 2014; NRC, 2012, p. 42). Another example is the effect of visual literacy on "analyzing and interpreting data." This includes using "graphical interpretation… to identify the significant features and patterns in the data" (NRC, 2012, p. 51). In other words, scientists and students learning science must be able to make inferences about trends in data based on graphs and diagrams. When Shah and Freedman (2011) examined the effect of content familiarity and graph comprehension skills on inference generation in undergraduates at the University of Michigan, it was found that those with high graph comprehension skills were more likely to make inferences about the main effect communicated in a graph. Those with greater visual graphical literacy, a facet of visual literacy in science, were better able to interpret data presented in a graph.

Conclusion of Impact

The perceived divide between verbal expression and visual expression has existed since the creation of the Phoenician alphabet (Brumberger, 2007). If this is so, why is visual literacy so critical now? As noted throughout the history section, education is directed to produce citizens prepared for the economic future. In this moment, providing that education demands visual literacy. The world is becoming increasingly rife with visual information. Dallow (2007, p. 102) declared that, "Education has a requirement to meet in practical ways the unfolding demands of our living visual culture."

Perhaps the belief that modern learners are "digital natives" has led to the perception that they are capable of producing an array of visual and often digital representations of data without explicit instruction (Silverman & Piedmont, 2016). However, many teachers know if you want to be sure a student can do any skill, you must teach them it. While visual literacy experts are lobbying for greater visual literacy education in secondary schools, it is not meant to be at the expense of other forms of literacy. The vision is for a greater balancing of word and image in literacy education so that students are best prepared for the future demands of higher education, career, and citizenship (Brumberger, 2007).

Instructional strategies for integrating visual literacy into science education

When it comes to visual literacy, we cannot expect students to do something they have not been taught to do. Visual literacy, like any literacy, must be explicitly taught for student success. Much like exposure to print or verbal language does not ensure print or verbal literacy, visual literacy skills can not be reliably acquired by exposure alone (Brumberger, 2007). The literature review component of Coleman and Dantzler's (2016) study on frequency of graphical representations in science trade books indicated that visual literacy skills are not natural and must be taught since multimodal media is considered more complex that single mode media such as a print-only text. Thus, science educators must consciously design their coursework to develop visual literacy skills in students.

Effective backwards design of any curricular materials requires that the end goal for what learners can do is aligned closely with their formative and summative assessments (Little, 2015; Offerdahl et al., 2015). A study measuring the effects of visual literacy instruction in a biology course revealed that misalignment of practice with assessment resulted in learner's not being able to perform the desired task (Arneson & Offerdahl, 2018). This illustrates that for effective learning and assessment of visual literacy to occur, visual literacy growth must be the intention throughout the entire planning process from selecting texts to teaching visual conventions in science to providing practice opportunities to students. Backwards design that prioritizes visual literacy skills in science class also communicates to students that those skills are inherent in the discipline of science (Offerdahl et al., 2015). Further, many special educators and English learner educators will emphasize how imperative keeping instruction visual is for their students to thrive (Wright et al., 2015). However, it does not follow that those skills are naturally acquired or that all visuals are effective in aiding instruction. So, if a struggling learner or EL student encounters a poorly constructed graphic they are more likely to be confused since they may not yet have the skills to link context from the print to the visual upon which they are relying. Thus, ineffective visual literacy education or poor resource selection can harm the students who may need the most help to succeed in challenging content courses like science. It is clear that for all students to thrive in the visually demanding discipline of science, visual literacy must be incorporated at all levels of curricular design.

On selecting quality texts

Once an end goal for visual literacy achievement has been identified, resources must be identified to support that learning. There are two primary concerns in selecting resources for use in visual literacy education: aligning the resource to the discipline and ensuring that the resource is "readable" by learners with limited content knowledge and visual literacy skills.

When considering the visual representations used in a resource, clarity is priority. Clarity of communication does differ by representation but some suggestions may be similar across media. Kragten et al. (2013) found that the number of components was negatively related to the learner's comprehension of a diagram. For example, diagrams with more errors communicated the process shown more clearly and thus reduced comprehension errors. Familiar components may help students comprehension since they activate familiar schemas in the learner's mind. Arrows and labels were two such familiar components that students cited as helpful in comprehending diagrammatical information in McTigue and Flowers study of learner's perceptions of diagrams (2011). Students prefer organized graphical representations in text where organization is defined by students as both the lack of clutter in a representation and clear connections between the different visual components of a representation. More abstract representations can certainly be used but will require more scaffolding when asking students to complete interpretation tasks.

It is advisable to consider how visuals are used in specific disciplines and what an instructor wants students to be able to do with them (Little, 2015; Arneson & Offerdahl, 2018). Coleman and Dantzler (2016) found that the types of graphical representations common in each of the three major disciplinary areas differ with the exception of timelines which are present in all three. Because of this, texts should ideally contain graphical representations relevant to that disciplinary area to help build students competency in both visual literacy and content. For example, the systems level focus of earth and space science often relies on illustrated process diagrams. As such, earth and space science teachers would benefit from teaching from texts or other resources that utilize such diagrams. If an educator anticipates students dissecting plants or animals and labeling structures in a biology course, students may benefit from learning how to distinguish labeled structures in photographs or illustrations first. As mentioned, one cannot assume a student knows how to learn from a multimodal resource or demonstrate their learning in multimodal form without teaching them those skills.

One tool for evaluating resources that include graphical representations is the "Graphic Rating Tool" or GRT developed by Roberts et al. (2014). This tool is useful because it reminds educators to consider both the readability of the graphics and the relevance to the discipline. The GRT emphasized material that is aligned to the content standards, credibly sourced, accurate, ideally appropriate for a read-aloud, appropriate for independent reading at grade level, and has graphical representations that extend or support the meaning of the print text. If all criteria are met, the GRT asks that the graphical representations contained therein have clear labels and scaling and easily understood symbols. Utilizing a formal tool like the GRT may help instructors who are unsure where to start with material selection.

A second set of guiding questions developed by Wright et al. (2015) recommends evaluating resources to be used with EL students by asking the following questions:

1. Does the graphic model a [whole] system?
2. Is the graphic near relevant text?
3. Does the text reference the graphic [explicitly]?
4. Does the graphic have descriptive captions?
5. Does the graphic or its caption contribute clearly to the content knowledge? (p. 43-44)

If the answer to all five questions is yes, the graphical representation is advisable. If not, the graphic may still be used if teachers should plan to scaffold the areas that did not receive a "yes" answer. For example, if the caption of a graphic is not relevant to the print text or content knowledge, teachers can model rewriting the caption to improve or even ask students to do so.

The unfortunate reality of education is that not all texts with visual representations are ideal for visual literacy education. While visual literacy is key to success for students' learning and futures, not all graphical representations are effective in contributing to this learning. However, when students are equipped with both the right skills and the right visual resources, the cognitive load of learning new material can actually be reduced and aid in language and content knowledge acquisition (Wright et al., 2015). Teachers should be intentional about text or other multimedia selection in science classes to fully develop learners' potential in visual literacy.

Teaching visual conventions

While having quality graphical texts is key to developing visual literacy in a class, alone it is not sufficient (Roberts et al., 2014). Once a text has been selected, educators must shift to considering how to teach the relevant visual conventions. Visual conventions include how to use arrows in a process diagram and how to scale and label axes in a graph. Silverman and Piedmont (2016) equated the necessity of learning both the mechanical conventions of visual literacy and the conceptual use of visual literacy to decode and encode information to print literacy: in print literacy, handwriting and typing, the mechanical conventions, are foundational in being able to execute the decoding and encoding functions of writing. The individual components of various graphs and diagrams commonly used in each science discipline serve as the essential visual conventions for that discipline. Instructional methods supported by research for doing so including pre-assessment, teaching the vocabulary of visuals, think-alouds, illustrating the importance of visual literacy skills in science, teaching scope and limitations of various diagram types, focusing on one visual convention at a time in instruction, and addressing scaling.

Because prior content knowledge and knowledge of visual conventions affects the ability to encode information from graphical representations (Shah & Freedman, 2011), teachers should pre-assess learners on both prior knowledge of visual representations and content knowledge (McTigue & Flowers, 2011). Firstly, the interaction of these factors affects a student's ability to execute visual literacy tasks (Kragten et al., 2013). Secondly, this will pinpoint what areas must be addressed in explicit instruction and scaffolding by the teacher (Kragten et al., 2013). Thirdly, students will likely come to class with a wide range of ideas and preconceptions about different graphical representations that should be addressed directly if inaccurate (Roberts et al., 2013).

Visual literacy is so multi-faceted that pre-assessment may be challenging. It may behoove educators to pre-assess one element that they seek to teach at a time. For example, because secondary graphical literacy includes "reading, interpreting, drawing, comparing, and evaluating aspects" (Ozmen et al., 2020, p. 272), a teacher may find it most effective to pre-assess only the comparison aspect. With that in mind, it should be noted that students are most successful in the reading aspect of visual literacy, that is understanding what is explicitly shown in the graph. It may be fair for a teacher to assume they can do this depending on the class but not fair to assume that all students will be able to interpret the significance of a graph or draw a diagram themselves. Consequently, higher-level tasks are the ones more important to pre-assess. Regardless of whether the task an educator seeks to teach is a lower-order or high-order one, pre-assessments for both graphical and content knowledge are widely available online, often for no cost. Teachers may easily find these by searching for the visual convention or content they seek to instruct followed by the phrase “pre-assessment” or “pre-test.” Alternatively, teachers can also informally assess a whole class or small groups in think-alouds as one informal method to assessing student understanding of graphical representations like diagrams as proposed by McTigue and Flowers (2011). Regardless of the method of pre-assessment, teachers should know what students already know and with what they most struggle.

Once a teacher knows the capabilities of their students, developing vocabulary is the next recommendation. Students need to be able to define the visual representations they are looking at to understand its purpose and communicate its meaning to others (McTigue & Flowers, 2011). While written assessments can also be utilized to explore this, they provide less "insight into students' meaning-making processes" (McTigue & Flowers, 2011, p. 586). Students need the language of visual conventions to explain their thinking to classmates as part of social learning, to the teacher in assessment, and to themselves as part of creating mental models of scientific processes. Without it, they rely on phrases like "those little blips" which may describe the graphic but are not universal and may be too subjective for effective communication of learning

(McTigue & Croix, 2011). Therefore, teachers should directly instruct the elements of a visual like arrows, captions, etc.

Modeling critical "reading" of a piece of multi-modal media in a think-aloud is one effective option for visual literacy instruction. A teacher may model "how [they] would read the data, interpret its meaning, and understand its implications, both intellectually and personally" (Lamb et al., 2014, p. 26). This can help students understand how expert "readers" of images make their conclusions (Roberts et al., 2013). Educators should explain how they interpret abstract information like symbols as well as inferences they make that are not explicitly shown in the graph such as context (Kragten et al., 2013). Further, teachers can talk through what the graph does not show and what questions it triggers in their minds to help students understand how graphics are a part of the scientific inquiry process (Roberts et al., 2013). Teachers may also discuss why the author chose to use a certain type of graphical representation over other types (Roberts et al., 2013).. One specific element of many graphical representations teachers should address explicitly is scale. Not only is it one of the major cross-cutting standards in NGSS (NRC, 2012), secondary age students are better developmentally able to conceptualize the various representations of scale in science graphics (Roberts et al., 2014). Think-alouds can also be a good opportunity to investigate credibility (Lamb et al., 2014; Kragten et al., 2013). When investigating bias and credibility, students may benefit from seeing both good examples and poor examples of scaling and labeling. Students will not intuitively catch when a graph uses biased scaling to display the data in a certain way and must be taught this skill (Ozmen et al., 2020).

Teachers should make it clear that strong readers in science read the visuals as well. This is imperative because elementary teachers and parents sometimes discourage looking at the graphics in an effort to develop student's print literacy skills (Roberts et al., 2013). To demonstrate to students how essential graphics are in text, McTigue and Croix (2010) proposed providing students a portion of text alongside a graphic provided in the text and asking them to identify what information is presented in both print and graphic and what is unique. Given the proportion of information found only in graphics and not in texts in secondary science materials, students will see that graphics are essential to their understanding when learning from text. Ideal visual literacy education "guides students to find the value in graphical representations" as opposed to leaving them thinking they are unimportant in school and life beyond (McTigue & Croix, 2010, p. 22). Teachers can certainly choose other ways to illustrate the importance of visual literacy in science to students, but should take care to make this learning student-centered.

Not only do students need to learn the importance of visuals in science as well as the specific conventions for the forms of visual literacy they utilize, they also need to know the "scope and limitations" of different visual modes (Kragten et al., 2013). For example, if bar graphs are being taught, students must know what bar graphs show and what they in turn can show in a bar graph. To further illustrate the different purposes of different representations, McTigue and Croix (2010) proposed showing students different representations of the same topic. For example, a captioned photo of a volcano could be shown alongside a cross-cut of a volcano and a process diagram of the rock cycle which includes a volcano. Students will see that different representations can contribute to their learning and understanding in different ways.

Next, effective scaffolding in the visual literacy of science requires focusing on one level of abstraction or scale at a time with learners. For example, a chemistry teacher would benefit from teaching the visual convention of the Bohr model of an atom in isolation before asking students to navigate a figure that shows interactions between Bohr model atoms. Learners can navigate figures that have multiple levels of scale, abstraction, and representation but familiarity with the individual elements helps them to do that (Offerdahl et al., 2017). Educators should attempt to break any mode of visual representation used for the first time into its core parts and ideally use a simple but well-labeled version.

Lastly, one of the key misconceptions students make in learning graphing is that scaling is literal in visual representations. Scaling is difficult for secondary students all the way through college so this area must be explicitly addressed in instruction (Ozmen et al., 2020). Teachers may address this in many ways: through a think-aloud, in a written protocol provided to aid students, in guided questions, and in formative feedback.

One model of teaching diagram comprehension developed and tested by Cromley et al. (2013) supported several of the instructional methods described here. Their protocol involved a 10th grade teacher who had received professional development teaching two classes with a diagram comprehension workbook and teaching two classes "business-as-usual." The workbook and instruction involved identifying and labeling the parts and functions of different diagram types and tips for decoding diagrams, which was both vocabulary instruction and focusing on one visual convention at a time. The teacher also provided feedback on student answers on these tasks. Students who completed the diagram decoding workbook in class alongside their regular curricula were better able to identify parts of different biology diagrams and better able to complete two-step questions using diagram conventions of other biology diagrams. Since the workbook focused solely on learning the basics of visual conventions at a lower-cognitive level, it can be seen that even a basic understanding has the potential to allow students to better utilize diagrams in learning. Thus, teaching the visual conventions directly is essential in science visual literacy education.

While there were many considerations described here for teaching the basics of reading visual representations in science, the intent is not to overwhelm educators. Ideally, teaching visual conventions should be embedded into existing reading comprehension instruction (McTigue & Flowers, 2011). While the many considerations listed here are important, they are most accessible to teachers when woven into existing instruction on texts that may already be used in class. As students develop their lower-order visual literacy skills through this reading instruction, they will be more prepared for the challenge of higher-order skills like drawing inferences and creation of their own models.

Practicing using visual conventions

When it comes to practicing visual conventions, many resources for science visual literacy education exhibit a pattern of students first reading visual representations, then moving on to interpreting and evaluating representations, and finally producing their own. The higher level challenge of interpretation, evaluation, and creation of graphical representations requires intentional scaffolding by instructors as these are less likely to develop naturally in science education. This is supported by research of Ozmen et al. (2020) in their findings that 8th grade Turkish students were successful in reading graphs and somewhat successful in interpreting them but not very successful in drawing their own. Offerdahl et al. (2017) posited that building these higher level skills, despite their challenge, better helps students develop mental models of scientific processes as well for lasting learning. Consequesntly, teachers must afford students opportunities to develop these skills intentionally in class.

These higher-level skills like interpretation and synthesis are essential for strong science students because those with expert visual literacy skills utilize graphical representations differently than non-experts. Harsh et al. (2019) conducted an eye-tracking study of biology undergraduate students, graduate students, and faculty exploring their examination of graphical data representations. Non-expert viewers were more likely to need to rely on cues from question and answer prompts to guide their examination and were less equipped to understand graphical information without this type of prompting. However, expert viewers automatically knew to look at cues like titles, captions, and data sources to inform the context and were better able to interpret graphical information. Since most visual data learners will encounter as adults will not be accompanied by guiding questions, students must be able to develop visual literacy skills high enough to engage in critical evaluation. Based on results from their eye-tracking study and concomitant literature review, Harsh et al. (2019) recommended instruction in the purpose of graphs, the construction of graphical representations, and self-reflection on graphical representations.

Although some visual literacy skills and conventions may develop over time with students’ high contact with images, these skills are usually of the lower-order. The greater challenge for students is practicing higher order skills like synthesis of graphical representations and critical evaluation of data presented visually as supporting or refuting a hypothesis. (Little, 2015; Arenson & Offerdahl, 2018). As Mctigue and Flowers (2011) all indicated that, "exposure does not ensure mastery." These higher order skills place greater cognitive strain on students' working memory. The way to reduce that cognitive load is to increase their discursive visual fluency, which is their ability to decode and encode visual representations and generate mental models from them (Offerdahl et al., 2017). Producing graphics is also key for helping students understand better the abstract visual conventions that make scientific diagrams different than pictures (Mctigue & Flowers, 2011). Arneson and Offerdahl (2018) acknowledged that students need to practice visual literacy skills to gain proficiency but inferred from their results that students would only practice what was emphasized in their summative assessments. As a result, they proposed that teachers must tightly align visual literacy aims of each unit with visual literacy tasks on that unit's summative assessment. Aligned with the recommendations of Harsh et al., (2019) educators should provide students opportunities to create their own visual representations and evaluate their work as well as that of their peers.

Much like learning to identify the visual conventions, learners will benefit from direct instruction on creating models. At first, teachers may model how to create visual representations. Then, when moving between interpretation of visual representations and having students create their own, teachers may collaborate with students on part-instructor generated and part-learner generated models. Quillin and Thomas (2015) identified drawing, that is creating a learner-generated visual representation, as a natural progression of interpretation skills because most graphical creation tasks students are asked to begin with partially instructor-generated drawings that students must interpret and complete. That said, when students move on to creating completely student-generated visual representations, teachers must provide them with clear expectations for the task in both what visual conventions should be used and what content must be represented.

Students may enter class with the misconception that the best way to represent information in graphical form is ruled by aesthetic sensibilities rather than the function of different graph or diagram types. Students will benefit from learning which graph types align best with which forms of data. This foundation can be laid when teaching visual conventions by having students identify graphical representations that are a strong way to represent data and which ones are not (Ozmen et al., 2020). Once students know which forms are appropriate for which type of information, they are more prepared to create their own. This is also something students should look for when evaluating their own and peers' work.

When students have moved beyond partially instructor-generated models to making their own entirely, teachers may increase engagement by providing freedom in what topic in a given unit or diagram type, as long as appropriate, to create to represent information. Also to the end of student engagement, educators should facilitate visual representation tasks that are like those students may make in a non-school context as this aids in increasing the relevancy of the work to students (Roberts et al., 2013).

As students work on their own graphical representations, teachers can support their efforts by providing quality mentor texts that reflect the types of visual representations your students are creating in content and type of graphic (Roberts et al., 2013).While it is true that exposure to quality texts and visuals alone is not enough to teach students how to create visuals, they can serve as an aid in creation and reflection.

Some students may find that the creation of visual representations is a skill they acquire relatively quickly. If this is the case, Smith and Robertson (2021) suggested students not only create graphical representations but also learn how to integrate them into text. This deepens their understanding of how print and visual media support one another in a text. Since utilizing both verbal and visual information aids in learning, these students will continue to deepen their understanding of both content and visual literacy skills. Additionally, this type of task is more authentic to actual tasks students may be asked to complete in their careers.

Once students have begun producing their own visuals, they need feedback to grow in content and visual literacy skills (Roberts et al., 2013; Roberts et al., 2014). Feedback can be facilitated in a number of ways. Lamb et al. (2014) proposed utilizing feedback in pairs or a gallery walk which provides a quick, efficient way for students to share ideas and provide critical feedback on how well a person's representation communicates. Like other elements of visual literacy education, teachers should model how to provide helpful peer feedback and can offer a list of questions to help guide peer discussion (Roberts et al., 2013). Teachers should also provide clear feedback to students aligned with the clear expectations set for the task.

When reflecting on their own work or reviewing a peer’s work, students should be guided to ensure visual representations are clear to even those who may not have strong content knowledge as this is again more authentic to real career tasks. It is also specifically appropriate in science because science communication operates typically in one direction as the general public will not be questioning the original authors on research on what their figures mean, students striving to learn how to use visual representation in science should also strive to communicate all necessary information in their figure (Trumbo, 1999).

Despite the best intentions of educators, challenges will no doubt arise when asking students to produce their own graphical representations due to the high cognitive demand. However, Quillin and Thomas (2015) identified many effective, research-supported interventions in their drawing-to-learn framework for model-based reasoning in biology. This framework is rooted in data indicating students learn more combining visual and verbal information in practice than verbal information alone regardless of their preferred learning mode. Within their framework, they identify three areas for intervention instructors may use when asking students to practice using visual conventions: affect, visual literacy, and model-based reasoning.

Engaging students in production tasks is most effective when students' affect, or emotional state, is open and ready to accept visual convention practice tasks as useful in content and important in the discipline. Proposed interventions by Quillin and Thomas (2015) for encouraging positive affect towards visual learning tasks include the educator's attitude, the value of the task, recognizing students' self-efficacy, and engaging student interest. Educator's attitude should communicate the educator's positive value of drawing in science and clarify that the intention is to show science learning, not to identify the strongest artist. The value of the task must be communicated throughout the class by heavy referral to visuals in instruction and designing practice tasks that require creation of visuals to be successful. The student's self-efficacy should be promoted by defining clear expectations for the task and associated grading if applicable as well as modeling those expectations. Finally, student interest should be piqued by increasing sufficient time, space, and encouragement as well as student choice.

Quillin and Thomas (2015) recommendations for improving visual literacy skills are closely aligned with the many other suggestions made here such as explicitly defining symbols used in each discipline, having students translate text into visual and vice versa, and providing opportunities to complete similar tasks with similar tools as will be assessed summatively. They uniquely suggested improving visual literacy skills by proposing that students practice translating one visual into another visual at a different scale to aid in deeper understanding of scale in visual representations.

The last area of recommended interventions identified by Quillin and Thomas (2015) focus on improving the model-based reasoning associated with interpreting and evaluating visuals. This focuses on modeling both creation of visual representations and analysis of their structural features, prompting students to use visuals they created to solve problems given them, asking students to provide peer feedback on improving models, and asking students to self-reflect the quality and accuracy of their models.

The visual literacy skills students can use in science are limited to their instructional opportunities (Offerdahl et al., 2017). The responsibility is for science educators to equip students with strategies for utilizing the many forms of visual representations authentically present in science. This can only be accomplished if students are given exemplary mentor texts, taught visual conventions explicitly, and provided with the opportunity to practice higher-order skills like interpretation and creation of visuals consistently.

CHAPTER III: DISCUSSION AND CONCLUSION

Summary

Though science education is currently split into three distinct disciplinary areas with unique reform concerns, all are supported by the integration of visual literacy education. Students who have been equipped with visual literacy skills are better able to learn science concepts, demonstrate their learning on assessments, and rise to the expectations of career and citizenship which has long been the focus of secondary science education reform. Aside from the economic motivation behind science reforms, history also points towards a trudging move towards practices of science over rote knowledge. Visual literacy supports this end by allowing students to gather information and make inferences from increasingly visual sources, better generate mental models of phenomena, and encode explanations of phenomena in multimodal form.

Students can easily find their working memory overloaded if they are not prepared for the demands of visual media in science. Educators can address this concern by integrating visual literacy education into current science education. The two focuses of integrating visual literacy in science are teaching students visual conventions utilized in science communication and building in opportunities for practice and assessment of using visual conventions themselves. As many master teachers know, students cannot be expected to know or do something they have not been taught. Explicit instruction and clear backwards design that tightly aligns assessment with learning is essential for students developing the desired proficiencies. By developing and utilizing curricula that teach visual literacy, students will be better prepared for learning and life.

Personal Application

From scouring schematics of broken analyzers during laboratory trouble-shooting to drafting models of experimental design for approval to assembling professional-grade posters for presentation of research, I was surprised how much decoding and encoding of visual representations I am doing as a scientist just out of my undergraduate experience. However, I was always able to keep up with the visual demands of analytical science. I took for granted the way I had accumulated these skills over years of art classes, advanced science coursework, and an engineer dad who took every opportunity to express his ideas on green graph paper to his children. Upon my entry in student teaching, I was shocked to find that the seventeen-year-olds in my high school placement were capable of graph creation and critical diagram analysis at a level almost identical to the twelve-year-olds in my middle school placement. How were so many students making it so far in secondary education without improving these key science skills?

I wondered how any students could be expected to do the authentic inquiry idealized by education researchers and administration alike without the ability to show their thinking visually or utilize visual sources of information deeply to generate questions, predictions, and explanations. I soon realized that because visual literacy was not a focus in the standards, even the most effective teachers with effective backwards design were not teaching or assessing their students on these skills even though they are non-negotiable in science and engineering careers and helpful in all fields. I too found it challenging to teach students how to improve without clear guidance. This research has affirmed my passion for visual literacy, illustrated its usefulness to students preparing for any line of work but especially STEM fields, and identified some research-backed strategies for teaching secondary students of all ages and abilities to improve their visual literacy skills.

It was disheartening to learn how many students struggle with visual representations even though they are a major part of assessment both at the secondary and college admission level. The lack of visual education was closing doors for students. Further, I felt for students who may have struggled with these elements of science before due to the high cognitive load of all the visual information provided. I suspect these students may have been encouraged to try harder and build “grit” while the root issue was that they had never received explicit instruction in these skills. Despite this, I am optimistic about the emphasis on model creation and utilization of visual sources in present standards. My hope is that all science educators find this shift improves their students’ capacity to learn, ability to show their learning, and excitement for science renewed as the barrier of heavy visual communication is lifted through this learning.

Professional Application and Importance

Because all students have finite working memory capacity, it can be easy to overwhelm them with visual decoding and encoding tasks. Research indicates familiarity with visual representations and their requisite parts aids in reducing the cognitive load and demand on working memory. Therefore, the first priority for teachers is to select quality mentor texts when possible and teach the decoding of the visuals within. For example, when using a water diagram a teacher may need to not only think-aloud how to figure out what is being shown but also how it is being shown. Explaining what arrows indicate, what common symbols represent in the discipline, etc... helps students understand that visual conventions are purposeful and how to read them. Students must be provided opportunities to decode visual representations on their own following this. As students build proficiency in decoding visual representations, teachers must then move to teaching the encoding of visual representations. Students can be scaffolded to create their own visual representations by beginning with partially instructor-generated representations that they then complete on their own. Advanced students can be further challenged by creating truly multi-modal texts wherein they incorporate their visual representation back into a print text. All these tasks do not and should not have to be completed separately from their typical content science education. In fact, teachers can teach decoding visuals as they teach the content. They can ask students to complete decoding and encoding visual representation tasks when assessing student learning of the content itself. The strongest visual literacy education educators can provide would be integrated into usual print literacy and content tasks they already utilize.

Limitations of Research

While there is no shortage of research on the prevalence of visual representations in educational materials, assessments, advertisements, workplaces, and nearly every facet of student's daily lives and futures, there are limitations in the research of how the encoding and decoding differs by type of visual representation. One study indicated that learners' familiarity with a specific type of visual, for example a cutaway diagram, improved their comprehension of other diagrams using similar conventions but only to diagrams using similar conventions (Kragten et al., 2013). Along these lines, further research investigating how to better activate prior knowledge of one diagram type and its conventions to a different diagram type would be valuable.

Additionally, there was a dearth of research-based instructional strategies for teaching and assessing learners on specific areas of visual literacy such as graphing. This is despite the research indicating students need to be explicitly taught all the areas they are expected to use and the skills are not completely transferable among different types of visual representations. Further, almost all the research available on both the impact of visual literacy, as well as best instructional practices, involved primarily white, English-speaking student populations. As racial equity is a growing concern in education, verification that the same trends and practices are effective for students of all cultural and racial backgrounds is imperative. This work would be of particular interest to English language educators who utilize visuals heavily and often propose using them in general education as a way to scaffold for English learning students.

One final area of potential research may be on how special education students utilize visuals and where they acquire these strategies. Much like English language educators, special educators often stress to their general educator colleagues the importance of making content "visual" for students with special education needs. It is found in the research that providing visual representations can actually increase the cognitive load on students yet special educators indicate making things visual for students with special education needs can be an effective way to scaffold. Therefore, research exploring what strategies students with special education needs use and where they acquire these strategies would provide useful information for teachers attempting to scaffold their visually demanding science coursework.

Conclusion

Research indicates both the high prevalence of visual representations in science learning materials that contain information not present in print and the high cognitive load associated with multimodal encoding and decoding. As a result, we cannot expect students to be successful with intentional development of their visual literacy skills. Science educators can best help their students thrive in science class and life by explicit instruction of visual literacy skills starting with defining visual conventions and moving into scaffolding them into creation of their own visual representations. By doing so, students will be better able to meet the demands of inquiry learning in science and the modern workplace which has long been the goal of science education as dreamed by scientists and education reformers alike.

References

Arneson, J. B., & Offerdahl, E. G. (2018). Visual literacy in bloom: Using Bloom's taxonomy to support visual learning skills. *CBE Life Sciences Education, 17*(1), ar7–1-8. https://doi.org/10.1187/cbe.17-08-0178

Bintz, C. (2016). Visual literacy: does it enhance leadership abilities required for the twenty-first century? *Journal of Visual Literacy, 35*(2), 91–103. https://doi.org/10.1080/1051144X.2016.1278087

Bucchi, M., & Saracino, B. (2016). Visual Science Literacy: Images and Public Understanding of Science in the Digital Age. *Science Communication, 38*(6), 812–819. https://doi.org/10.1177/1075547016677833

Burmark, L. (2008). Visual literacy: What you get is what you see. In N. Frey & D. Fisher (Eds.), *Teaching visual literacy using comic books, graphic novels, cartoons, and more to develop comprehension and thinking skills* (pp. 5-25). Corwin Press.

Brumberger, E. R. (2007). Making the strange familiar: A pedagogical exploration of visual thinking. *Journal of Business and Technical Communication, 21*(4), 376–401. https://doi.org/10.1177/1050651907304021

Chiappetta, E. L. (2007). Historical development of teaching science as inquiry. In J. Luft, R. L. Bell, & J. Gess-Newsome (Eds.), *Science as inquiry in the secondary setting* (pp. 21-30). NSTA Press.

Coleman, J. M., & Dantzler, J. A. (2016). The frequency and type of graphical representations in science trade books for children. *Journal of Visual Literacy, 35*(1), 24–41. https://doi.org/10.1080/1051144X.2016.1198543

Cromley, J. G., Perez, T. C., Fitzhugh, S. L., Newcombe, N. S., Wills, T. W., & Tanaka, J. C. (2013). Improving students' diagram comprehension with classroom instruction. *The Journal of Experimental Education, 81*(4), 511–537. https://doi.org/10.1080/00220973.2012.745465

Dallow, P. (2007). The visual complex: Mapping some interdisciplinary dimensions of visual literacy. *In Visual Literacy* (pp. 91–103). https://doi.org/10.4324/9780203939574

Dodick, J., & Orion, N. (2003). Geology as an historical science: Its perception within science and the education system. *Science & Education, 12*(2), 197–211. https://doi.org/10.1023/A:1023096001250

Fernández-Fontecha, A., O'Halloran, K. L., Tan, S., & Wignell, P. (2019). A multimodal approach to visual thinking: the scientific sketchnote. *Visual Communication (London, England), 18*(1), 5–29. https://doi.org/10.1177/1470357218759808

Fingeret, L. (2012). Graphics in children's informational texts: A content analysis. (Unpublished doctoral dissertation). Michigan State University, East Lansing, MI.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education*, *76*(4), 548–554. https://doi.org/10.1021/ed076p548

Hannus, M., & Hyönä, J. (1999). Utilization of illustrations during learning of science textbook passages among low-and high-ability children. *Contemporary educational psychology*, *24*(2), 95-123.

Harsh, J. A., Campillo, M., Murray, C., Myers, C., Nguyen, J., & Maltese, A. V. (2019). "Seeing" data like an expert: An eye-tracking study using graphical data representations. *CBE Life Sciences Education, 18*(3), ar32-1–ar32-12. https://doi.org/10.1187/cbe.18-06-0102

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education, 70*(9), 701–705. https://doi-org.ezproxy.bethel.edu/10.1021/ed070p701

Kragten, M., Admiraal, W., & Rijlaarsdam, G. (2013). Diagrammatic literacy in secondary science education. *Research in Science Education, 43*(5), 1785–1800. https://doi.org/10.1007/s11165-012-9331-0

Lamb, G. R., Polman, J. L., Newman, A., & Smith, C. G. (2014). Science news infographics: Teaching students to gather, interpret, and present information graphically. *The Science Teacher, 81*(3), 25–30.

Lagowski, J. J. (1988). The continuing attempt at reform in science education. *Journal of Chemical Education, 65*(1), 1. https://doi.org/10.1021/ed065p1

Lewis, E. B. (2008). Content is not enough: A history of secondary earth science teacher preparation with recommendations for today. *Journal of Geoscience Education, 56*(5), 445–455. https://doi.org/10.5408/jge_nov2008_lewis_445

Little, D. (2015). Teaching visual literacy across the curriculum: Suggestions and strategies. *New Directions for Teaching and Learning, 2015*(141), 87–90. https://doi.org/10.1002/tl.20125

McTigue, E., & Croix, A. (2010). Visual literacy in science. *Science Scope (Washington, D.C.), 33*(9), 17–22. https://doi.org/10.2505/3/ss10_033_09

McTigue, E. M., & Flowers, A. C. (2011). Science visual literacy: Learners' perceptions and knowledge of diagrams. *The Reading Teacher, 64*(8), 578–589. https://doi.org/10.1598/RT.64.8.3

Meltzer, D. E., & Otero, V. K. (2015). A brief history of physics education in the United States. *American Journal of Physics, 83*(5), 447-458. https://doi.org/10.1119/1.4902397

National Research Council. 2012. A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. Washington, DC: The National Academies Press. https://doi.org/10.17226/13165

Nguyen, T. (2020, August 12). How social justice slideshows took over Instagram. Vox. https://www.vox.com/the-goods/21359098/social-justice-slideshows-instagram-activism

Offerdahl, E. G., Arneson, J. B., & Byrne, N. (2017). Lighten the load: Scaffolding visual literacy in biochemistry and molecular biology. *CBE Life Sciences Education, 16*(1), es1–es11. https://doi.org/10.1187/cbe.16-06-0193

Ozmen, Z. M., Guven, B., & Kurak, Y. (2020). Determining the Graphical Literacy Levels of the 8th Grade Students. *Eurasian Journal of Educational Research, 86*, 269–291.

Quillin, K., & Thomas, S. (2015). Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. *CBE Life Sciences Education, 14*(1), es2–es2. https://doi.org/10.1187/cbe.14-08-0128

Roberts, K. L., Brugar, K. A., & Norman, R. R. (2014). Evaluating Texts for Graphical Literacy Instruction. *The Reading Teacher, 68*(4), 312–318. https://doi.org/10.1002/trtr.1321

Roberts, K. L., Norman, R. R., Duke, N. K., Morsink, P., Martin, N. M., & Knight, J. A. (2013). Diagrams, timelines, and tables-oh, my! Fostering graphical literacy. *The Reading Teacher, 67*(1), 12–24. https://doi.org/10.1002/TRTR.1174

Rosenthal, D. (1990). What's past is prologue: Lessons from the history of biology education. *The American Biology Teacher, 52*(3), 151-155. https://doi:10.2307/4449067

Serafini, F. (2015). Multimodal literacy: From theories to practices. *Language Arts, 92*(6), 412–423.

Silverman, K. N., & Piedmont, J. (2016). Reading the big picture: A visual literacy curriculum for today. *Knowledge Quest, 44*(5), 32–37.

Shah, P., & Freedman, E. G. (2011). Bar and line graph comprehension: An interaction of top-down and bottom-up processes. *Topics in Cognitive Science, 3*(3), 560–578. https://doi.org/10.1111/j.1756-8765.2009.01066.x

Sotáková, I., Ganajová, M., & Babinčáková, M. (2020). Inquiry-based science education as a revision strategy. *Journal of Baltic Science Education, 19*(3), 499–513. https://doi.org/10.33225/jbse/20.19.499

Stafford, B. M. (1996). *Good looking : essays on the virtue of images.* The MIT Press.

Trumbo, J. (1999). Visual literacy and science communication. *Science Communication, 20*(4), 409–425. https://doi.org/10.1177/1075547099020004004

Wright, K., Eslami, Z., Mctigue, E., & Reynolds, D. (2015). Picture perfect: Using quality graphics to support English language learners in science classes. *The Science Teacher (National Science Teachers Association), 82*(4), 41–46.

Yager, R. (2000). The history and future of science education reform. *The Clearing House, 74*(1), 51-54.

Yeh, Y.-F. Y., & McTigue, E. M. (2009). The Frequency, Variation, and Function of Graphical Representations within Standardized State Science Tests. *School Science and Mathematics, 109*(8), 435–449. https://doi.org/10.1111/j.1949-8594.2009.tb18291.x

Zacks, J., Levy, E., Tversky, B., & Schiano, D. (2002). Graphs in print. In *Diagrammatic representation and reasoning* (pp. 187-206). Springer, London.