

Drawing for Science Education

An International Perspective

Phyllis Katz (Ed.)



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Edited by

Phyllis Katz

University of Maryland, USA



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PREFACE AND ACKNOWLEDGEMENTS

I began to think about a book on the use of drawing in science education when I gave a presentation at a conference about how I used drawings for research in the science enrichment program I headed. It elicited heated criticism about the degree of inference in interpretation. Having majored in English during my first round of higher education, I knew I had spent many hours interpreting words and their implications. With fellow students I argued the meanings of phrases by Shakespeare, Milton and James Joyce interpreting the word images. I also developed a healthy respect for punctuation (we could say, graphical clues) as more than linguistic rules from tormenting grammarians. Those small commas could certainly help clarify meanings. One humorous example is the difference between, “Let’s eat Grandma,” or “Let’s eat, Grandma.” As a consequence of my language studies, I found these challenges about excessive inference in the use of drawing data curious. I understood all human communication as inferential in its interpretations, colored by context, gesture and tone. Meanings come from an interaction between the observer and a phenomenon interacting within a culture. Reviewing the literature on the historic use of drawings in teaching and learning science I was struck by how pervasive and important this method of information sharing has been. And yet there was a disconnection between modern science education and the use or study of drawing. There has been some renaissance with the influence of graphical interfaces from computers, but there was little evidence that drawing was valued, taught, or encouraged among the skills of science or science education research. The increased use of verbal/literary communication had taken center stage. When science education developed in the late 19th century drawing skills were a part of the school curricula. Students were expected to be able to illustrate their observations. Drawing faded as the 20th century progressed. Cameras became readily available and affordable. Standardized short answer testing was an efficient way to compare results for individuals and across countries. Curricula became crowded with new study areas. However drawing, with its eye-mind-hand coordination continues to offer us opportunities for science learning and teaching. It is one of multiple tools that we can use to teach and investigate what people are thinking.

The original call for this book was about drawings as data—learning evidence that teachers and researchers could use in science education. However as the chapters were submitted, I had the opportunity to think more deeply about the illustrators’ perspective and what the act of creating a drawing could mean to them. There are other books on the use of visual data. Pedersen and Finson (2009) edited a collection of examples of visual data for research in the general field of education. Later, they assembled a volume more specific to science education (Finson & Pedersen, 2013). Neither volume focused solely on drawings and their physical, mental, emotional and contextual effects, as well as contribution to both the creators and other interpreters. This book has gathered authors from around the globe working with drawing as one of their instruments. Some of their experiences coincide and some present us with alternate ways to use this tool.

As we have learned in social science research, a variety of methods can take us closer to consensus on what our students (or the public) is observing or retaining in the context of our work. I wanted to gather and provide evidence for what drawings have meant in science education. Furthermore, it is not at all clear to me that we can separate the learning of science from the act of drawing, whether by pen and pencil or, more recently, electronics. And that is part of the point in this book—that science and drawing have been intimately bound together. Drawing has been used to record (e.g. Audubon) to envision (e.g. Leonardo daVinci), and to invent (e.g. Alexander Graham Bell). In science education research, drawing has been used to gain insights into the illustrator’s content information, attitudes, values, beliefs and motivations.

In my own work, I had found drawing a non-threatening way to obtain information in the afterschool science program I developed and which grew to a national scope with NSF funding. In encouraging children and their families to engage in afterschool science, we explained how it would be different from most science programs in school. We offered more freedom to express the children’s own thinking of the world, smaller groups than the usual classroom, and lots of material manipulation. We also described the opportunity as one in which there would be no tests. That is one of the complementarities of out-of-school science education, or what I term *continual science learning* (CSL). Schools need to have data to show status and answer to their tax-paying or tuition paying public in terms of standards and goals. CSL settings concentrate on keeping excitement up, on developing identities as continually interested science learners, and in providing resources (places, materials, approaches) that may not be readily available anywhere else. And yet, we, too, had grant funders who wanted to know just what was being gained by being in our CSL science enrichment program. I turned to drawing because children do not associate it with testing. I was able to obtain thousands of drawings with no protest. Those of us who reviewed them were able to see trends of what made an impression on the children in terms of content and affect. I learned that this was a very limited use of drawing as a science skill.

I was intrigued by how White and Gunstone (1992) used drawings to better understand how their students represented connections and processes. I had followed the use of drawings in the 1980’s that were employed to develop evidence about gender bias and other conceptions about who did science (Chambers, 1983; Schibeci & Sorenson, 1983; Kahle, 1985). Working with Dr. Randy McGinnis at the University of Maryland on Project Nexus, we used drawings over the course of years to observe how the answers to “Please draw yourself teaching science,” and “Please draw you students learning science,” changed during and after the teacher preparation program (Katz et al., 2011, 2013). As I read the developing literature on the subject, I came to see that drawing continues to be an essential tool for science work and science education. Coincidentally, I had recently read Noah Gordon’s book *The Physician* (1986), set in the eleventh

century. It tells the tale of an English orphan who is driven by his interest in medicine to travel to Isfahan in Persia to study with the famous Avicenna. In this novel, the dedicated protagonist is nearly executed for his efforts to draw (from post mortem dissection) the physiology of a man who has given his permission for others to learn from him upon his death. Religion forbid it. Medicine suffered. How important drawing was before photography and electronic imaging. The physician in this book on science drawing is also a medical illustrator. Gary Wind is a surgeon who helps put the combat-wounded back together. He tells you in his own words (Chapter 4) how he melded his interests in drawing and healing. His textbook on the vascular system is a beautiful and finely detailed teaching tool (Wind & Valentine, 2013). Medicine needs drawings just as contractors need blueprints. All of science needs drawing. There was no one book that brought a variety of these rich multiple drawing uses together. This book had its start as a result of my accumulated experiences.

I read about work being done by my colleagues around the globe. Some have invented ways to interpret the communication of drawings. Some have asked questions that are new to the use of drawings in science education. Some are replicating studies and comparing results across cultures. I find it exciting.

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I have been fortunate to be able to work in science education and to contribute to the field. I thank Michel Lokhorst and his team at Sense Publishers for bringing to fruition the vision within my original book proposal. While I had personal contact with many of the authors, I approached others because of their work within our journals. I thank all of them, both those who knew me and those who trusted me sight-unseen, for sharing their use of drawings in our field.

I would like to acknowledge the late David J. Lockard. He encouraged me to become a researcher as well as a practitioner. David was a world expert on mushrooms, as well as science teaching. I think of him every time I make my stuffed mushroom recipe and of his wonderful course in medicinal and poisonous plants. I drew many times in that course. There was an added pleasure to his mentorship. My father had given me a copy of the UNESCO book, *700 Science Experiments* (1958) when I was a child. It was exciting to know that my graduate mentor was an editor of this childhood treasure. Randy McGinnis was my next advisor and mentor. I used drawing data in my dissertation on mothers as science teachers, revisited recently as a chapter on science teacher identity development (Avraamidou, 2015). Dr. McGinnis encouraged me to foster my own identity as a science education researcher as I led the team at the organization that was developing and delivering afterschool science options. Those were challenging years and it is a pleasure to see how our work has now coincided once again in this book. Randy has continued to use drawing as a data collection technique (Chapter 21). Most importantly, I have also been fortunate to have my husband, Victor, as a scholarly partner. We spend many hours discussing our work and its implications. For this book, in addition to collegial talks, he made time to input my edits, as he is a much speedier typist than I am. Together, we have been tolerant of how our work impacts on a quirky lifestyle of suppers and bedtimes that vary by how intense our projects and grandparent demands are.

There are several people who fostered this book in small but meaningful ways. When I exchanged emails with Kevin Finson, who has the two books cited above on visual learning in science education, his response to my wanting to produce another volume was to offer assistance, if needed,—a gentleman and a scholar. Julie Thomas and Donna Farland-Smith, likewise had preceded me in publishing about the use of drawings and were gracious in sharing their thinking.

There are people who have facilitated my work in pervasive ways. George Tressel was my first program officer at the National Science Foundation. After he left the Foundation we developed a friendship. He has been my guru in many ways and I have always appreciated his blend of philosophy and practical knowledge. We discussed this book's material among our many science education conversations. My children have always been a cheering team and are each teaching now in different ways. Sharon Katz Cooper is responsible for science education dissemination for one of our ocean exploration vessels. She and I have talked about the use of images in our work. My son, Ari, is generous with his thoughts on international teacher education, global needs, and technology. Our talks have included visual evaluation. Naomi teaches through art. A costume designer by training, she has studied the ways in which art communicates, making me more aware of intentional techniques. This has given me clues to consider in the unintentional—that is, what people draw to communicate science learning without an artistic product as a conscious result.

Most of the chapters in this book are research reports. There are, however, two essays that don't conform to that genre. One is the chapter mentioned above by Gary Wind (Chapter 4). The second is by a middle school teacher in Botswana. Shiellah Keletso tells us of an action research project in which she utilized drawings after finding Project Nexus' *DrawnToScience* website through an internet search. She was seeking a way to improve her teaching so that she could become a more inclusive teacher (Chapter 20). Both of these chapters bring to the reader a different perspective from that of a professional science education researcher. They enrich this book, meant to provide examples for both science education researchers and teachers, whether in classrooms or other learning settings.

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1. INTRODUCTION: DRAWING AND SCIENCE ARE INSEPARABLE

Drawing is a Human Expression for Teaching/Learning

The act of drawing is an act of recording. Science requires the recording of data to seek insights and patterns. The mind that contemplates recording in a place and with a medium that will be seen by others at a future time implies a mind that can conceive of a future and also believes in teaching/learning through communication. Some researchers believe that it is likely that this cognitive ability—in this case, provided by drawing data—marks the distinction between our species and other hominids (Suddendorf & Corballis, 2007). We humans could plan for a future we could imagine. We could record, build knowledge, and convey it to others we would never know. Long before the technologies of printing, photography, and digital imaging, drawing was the only way to create a representation of features, construction, orientation, or pattern. We see this in portraits, maps, and paintings of historic events. Children begin early in their lives to make marks in mud, sand or snow as well as with intentional crayons and other art materials (Anning, 1999). Where to present or leave drawings and how to create a medium with which to draw are themselves evidence of early consideration of the characteristics of materials—what we could choose to call nascent technology. The alphabets and numerals that were developed later are drawn symbols for already standardized language. In mathematics, the symbols combine as visual shortcuts of communication to describe relationships and patterns. Drawing has been essential to our intellectual development. Where would science be without the drawings of Copernicus, Da Vinci, Audubon, Darwin, Bohr, Watson, Crick and Franklin, in depicting models, processes, and possibilities? Many other examples of science illustration have been collected for examination (e.g. <http://hyperallergic.com/97027/when-art-was-the-scientists-eye-400-years-of-natural-history-illustrations/> or <http://digitalcollections.nypl.org/collections/pictures-of-science-700-years-of-scientific-and-medical-illustration#/?tab=about>).

As you will see in this book, drawing continues to have communication benefits that are different from those of writing. One of these benefits is accessibility. Creating drawings on rocks and other surfaces for information has been possible for many people in many places since pre-history (Chippindale & Nash, 2004). Recording verbal and literary data came relatively late in human history and began with immediate limits. We could not use writing as a communication tool before we had those standardized alphabetic symbols. Teaching these symbols for reading and writing was a guarded process before such education was considered a universal right. Scribes who could copy accurately were sought after and had years of training. In some cases scribes had a place among those with sacred talents. Calligraphers crossed the boundaries of science and art by applying their talents to embellished alphabets and illustrations. These were done frequently to enhance spiritual life with instruction and beauty. These products were commissioned by the wealthy. Availability of writing materials was a technological limitation. The opportunity to record and learn from data was thus limited to those relatively few in control of the power and wealth to obtain these writing materials and writing teachers. According to the critical theorists in our field, control of records is always bound up in the power structure of cultures (Treagust, Won, & Duit, 2014). I would agree that by limiting participation and viewpoint, we limit the development of science. Consider that for thousands of years, drawings were perhaps more democratic in science observations as pre or non-literate people picked up charcoal, sticks, ink, and pencils to draw out what they saw for others. From Dewey (1920), through Rutherford and Ahlgren (1989) to a recent report published for UNESCO (Tibbetts, 2015) educators state an interest in universal, quality education to empower democratic participation and personal, knowledgeable choice. Could more use of drawing advance this goal for students, teachers and researchers?

Writing has its communication difficulties, especially when unaccompanied by illustration. Lengthy word descriptions run the risk of the reader's losing track of the whole argument for a pattern description. Such descriptions in Indian and Arabic mathematics not only reduced participants to those who could read, but also ran the risk of copy replication errors—not to mention the loss of student attention! Euclid's illustrations endure, however. The introduction of mathematical symbols facilitated the comprehension of the flow of ideas in compact images and standardized communications among mathematicians (Katz & Parshall, 2014). Drawing can make learning accessible, can provide clarity, and may be more efficient than verbal descriptions in certain circumstances. In this book, for example, you will find data from young children and non-literate adults for whom descriptive writing is not an option.

We use drawings today when there is critical information to be conveyed quickly. This is especially true when it is important for speakers and readers of multiple languages to understand the message. For example, we have international road signs for drivers, as in Figure 1 and 2. Another example is air travel. When we sit down in an airplane seat, the signs above tell us when to fasten our seat belts and that we must not smoke. Words, even in two languages, are apparently not considered sufficient. In several of the chapters in this book, the authors reference the advantage of drawings where there are multiple languages among a group (Chapter 13, Stears & Dempster; Chapter 9, Caney, Humphrey & Bowker) or where children are too young to write their thoughts (Chapter 7, Dai, Chapter 12, Chang), or where schooling has not been available (Chapter 8, Tunnicliffe & Angshuman; Chapter 9, Caney, Humphrey & Bowker).



Figure 1. International road sign for “no U-turn allowed here”



Figure 2. International road sign for road work ahead

In human history, early illustrators provided us with data about their surroundings. They told us what animals they encountered. Evidence of the drawing impulse is widespread. We can see mammoths in the Chauvet cave in France, rhinos in the Coliboaia cave in Romania, kangaroos in Australia, cow figures in Namibia and India, or a jaguar in Brazil (Marchant, 2016). Scientists have found decorated tools in South Africa dated to tens of thousands of years ago. These convey, “I have put my mark on this tool as an individual who creates.” We drew before we could write. Recent evidence of ochre production in South Africa suggests that creating images made with ochre paint dates back 100,000 years (Henshilwood et al., 2011). The newer dating techniques are good examples of the leapfrog nature of technology and data availability in research. Carbon dating has been limited to organic materials. New techniques with inorganic materials allow for a broader range of exploration which can now include ochre, an extensively used early human drawing medium. Just as we find the earliest hominid remains in Africa, we are finding and dating the earliest drawings there. Our African roots are not only physical, they are intellectual and artistic as we should expect in defining “human” as an emerging species in paleontology.

The intent of those who drew so many years ago is unknown. While we find many animal pictures on cave walls, we do not know why they were put there. Are they records of successful hunts to sustain the human need for nourishment? Are they desires of the same? Are they pleas to spirits for appreciation or supplication? Are they the artistic impulse of random illustrators or purposeful records of dedicated scribes? We cannot yet answer these questions but we do know that the existence of the drawings is a visible activity—a record of humans who wanted to express their thoughts for themselves and others to see as in Figures 3 and 4 below. What was the purpose of the hand prints found recently in Indonesia, dated to 35,000 years ago? At the very least, they record that someone wanted to note a human presence. Inference continues to be a question in interpreting these visual data. I consider this issue in a later section of this introduction. Recently, a pictographic calendar supported the intent of Lakota Indians (Wyoming) to keep seasonal records confirming this particular communication process through images among people without a literature (Momaday, 2015). It is important to recognize that drawing is an early and continued form of communication across time and about the world into which drawing for science education is a subset.



Figure 3. Male figures. rock art, Kakadu National Park, Australia. Photo by Phyllis Katz, 1995



Figure 4. Animal figure. Rock art, Kakadu National Park, Australia. Photo by Phyllis Katz, 1995

THEORETICAL BACKGROUND

The primary theoretical consideration for the use of drawings is intertwined with theories of mind. We often use the language of images when we speak about our thinking: We have “viewpoints.” We have “insights.” We say, “picture this,” or “let’s focus.” We talk of “illustrating a point” and of “visualizing” a situation or a concept. The theoretical framework for drawing as data begins with evidence that we use images, at least in part, to think. In arguing that “image” in its pictorial sense is limited in terms of sensory input for mental processing, Pylyshyn (1973) nevertheless stated, “Imagery is a pervasive form of experience and is clearly of utmost importance to humans. We cannot speak of consciousness without, at the same time, implicating the existence of images”(p. 2). “Visual/spatial thinking involves purposeful use of your ‘mind’s eye’ to develop mental pictures or images,” wrote Alan J. McCormack (1988, p. 2). He continued to describe how this kind of mental imaging permeates all human thinking whether one is packing a suitcase, reading, considering chess movements, or planning global politics on a map. He notes that Frederick Kekulé visualized the benzene ring in a dream. McCormack related that many phenomena in today’s science are not directly observable, but need to be visualized to be understood. As Sousa (2001), wrote about learning and the brain for teachers, he told us that visual images work to process new learning and to store information. He related that the brain processes our inner images in the same way that it does when the eyes see something in real time. He tied this into the survival value of such a system. It is crucial to be able to “run by” our minds the possibilities for selecting the safest immediate or long term benefit to our choices. By 2014, we have access to Dual Coding Theory (DCT) that provides a mental processing framework for inclusive verbal and non-verbal brain activity (Pavio). More recently, neuroscientists with brain imaging tools have explored the hexagonal geometry on which spacial data appear to be mapped and are finding that there may be similar brain maps for other stimuli, networking with each other (Constantinescu et al., 2016). As technology develops new instruments for investigation, research brings us evidence that within our brains there is an interaction between highly developed visual imagery and verbal capacities. In practical terms, the theoretical support for gaining insights into people’s thinking suggests that it would be well to elicit images as well as verbal/literary information.

If we accept the theory of mind as largely image loaded, we then consider evidence for how drawing can reflect those images as one window on the mind—that what we draw is a representation of how we are thinking about our experience. Researchers and educators have concurred that drawings can provide information that may be elusive in other forms of inquiry (White & Gunstone, 1992; Bell et al., 2009). Klepsch and Logie (1982) studied Indian (North American) children using drawings as one of their data sources. They reported,

Unwittingly, he [the illustrator] sketches in some details of his own traits, attitudes, behavior characteristics, personality strengths and weaknesses. In other words, he leaves an imprint, however incomplete, of his inner self upon his drawing. Since drawing also reflects the person, the ideas of using it as a measurement of personality, of self in relation to others, of group values, and of attitude is not out of line...Long before written language existed, man scratched drawings on cave walls to record his feelings, needs, and actions. Drawing communication, then, is elemental and basic. It is also universal. (p. 6)

In 2005, Van Meter and Garner, published a literature review of “learner-generated” drawing in a broad range of school settings, seeking to provide evidence for its effectiveness as a teaching strategy. Writing of the interplay of text and illustrations in provided teaching materials, they speculate that

...the selection of additional elements, in this back and forth consideration, the two internal representations act as mutual constraints during construction of the mental model...When, drawing, the internal verbal elements are organized into a coherent representation. This representation then serves as the foundation for constructing the internal nonverbal representation. (p. 317)

They are concerned that researchers were not asking “if drawing can improve observational processes, support the writing process, or improve learner affect” (p. 315). We move into the question of how we remember what we experience in our continual processing of information. Supporting theories speak to the role of drawing and memory. After conducting a series of experiments to test for memory effects of drawing as a way to recall, Wammes, Meade and Fernandes (2016) found a strong positive effect compared to writing. They conclude that “the mechanism driving the effect is that engaging in drawing promotes the seamless integration of many types of memory codes (elaboration, visual imagery, motor action, and picture memory) into one cohesive memory trace, and it is this that facilitates later retrieval of the studied words.” As with other hands-on aspects of science education, the act of participating, and of being asked to pay attention to an aspect of one’s thoughts engages more neural networks. Landin (2015) wrote of her choice to include illustration in her college biology classes that “Creating a high-quality scientific illustration requires a thorough understanding of biological processes, anatomy, and structural diversity...If you wish to differentiate fir and spruce trees, look carefully at how the needles attach to the twig. It’s all there—if you just look closely and precisely.” In developing theory, it follows that drawing, using multiple senses, would impress the experience for later recovery. Learning about the world requires paying attention and banking concepts in memory—all moderated by context, both physical and social as described, for example, by Rosseler & Dentzau (Chapter 11) or understanding students’ interpretations of physics as Vander Veen has done (Chapter 2).

DRAWING AS DATA IN SCIENCE EDUCATION RESEARCH

I would like to be clear that while I believe that drawing is essential to science education, none of us in this volume have claimed it is to be used today as an exclusive data collection tool. Every author speaks to the need to have an illustrator's notes, interviews, or in one case, video recordings (Winter & Astall, Chapter, 22) to complement what is drawn, concurring for example, that drawing and writing elicited more information than drawing alone when English and Australian children were compared for what they knew about technology (Rennie & Jarvis, 1995) or that interviews and drawings are most fruitful in understanding children's drawings of scientists (Finson, 2002). In fact, as Winter and Astall point out, our verbal communications are so nuanced that gesture, facial expression, body posture and words increase the likelihood that what the illustrator intended to communicate is enhanced through the accompaniment of videotaped (visual) description, so readily available today. Is this not another example of the reason that science education researchers have long recommended triangulation of multiple methods and sources of data collection in order to offer the best possible interpretation of what is happening within a given context (e.g. Guba & Lincoln, 1989; LeCompte, & Preissle, 1993; Banks, 2007)?

Concerns about drawing as a data source center around the degree of inference (and therefore validity) that may be used in interpreting this data. (Di Leo, 1983; Farland & McComas, 2004). Chambers (1983), in describing his development and research with the "draw-a-scientist" procedure noted this issue. He concluded, "DAST is easier to administer than most tests; however, a number of interpretive difficulties may arise" (p. 264). Ways of addressing these issues have been to refine the drawing prompts in their specificity, to develop rubrics for coding agreement, and to have multiple coders who reach consensus among themselves for meanings, or to have multiple drawings done by the same participants to help establish the stability of mental images. I add here a personal observation as well. Having majored in English during my first round of higher education, I knew that I had spent many classes and many hours interpreting words and their meanings. It was not only poetry that brought my classes to multiple views of word images. I developed a healthy respect for punctuation as more than rules from grammarians out to torture students. Those little commas could certainly help. I find myself puzzled at this particular concern for inference in drawings used as data. All human communication is inferential in its interpretations. What is true has much to do with context, culture and the receiver's personal history. As a simple example of written inference confusion, I relate the following two examples: Driving along the PA turnpike, there was a flashing sign, "Trucks and busses right lane only." Does this mean that the right lane is exclusively for trucks and busses, or that all vehicles may use the right lane, but trucks and buses must? Convention tells us the latter, but what of foreign drivers who do not use this road regularly? What about a child's announcement, "Look, here comes mother!" Are we welcoming our maternal parent, or are we a six year-old who is warning his friend that they should get their hands out of the cookie jar? Interpretation will depend on context and tone. In using quantitative or qualitative research methods (or any combination thereof), we need to consider context, history, relationships, response energy or fatigue, timing among other activities. Social science research is as complex as people are. And we argue by our work with drawings that they are useful pieces of information toward understanding.

Researchers who collect drawing data describe the setting, participants and prompts, as well as images. Some are looking for trends and do so by collecting large numbers of drawings within an age group and about specific concepts (e.g. Bartoscek & Tunnicliffe, Chapter 5). Others look at changes before and after an experience (Stears & Dempster, Chapter 13; Keletso, Chapter 20; Caney & Bowker, Chapter 9). Researchers have sought the presence or absence of elements (Barak, Chapter 3, or McClafferty & Rennie, Chapter 14). Presenting the variety of uses is part of the purpose of this book

As recently as a hundred years ago, drawing was required as part of the school curriculum (Landin, 2015). As we teach science with a more democratic educational effort to greater numbers of people, drawing has taken a backseat to verbal/literary teaching and learning, which has developed efficient ways of scoring large amounts of data for many people. Drawing as a social science research method began in the early 20th century. There are authors in this volume who provide a detailed history but I include a synopsis here to indicate the length and development of the method. Florence Goodenough was the first to systematically correlate drawings of "a man" with the early intelligence tests that were being developed at that time (1926). Mead and Metraux mention using drawings in their landmark work on the image of scientists; however they provided no details of how they used them (1957). Chambers first utilized drawings to explore the images that children held of scientists (1983). White and Gunstone (1992) provided clear examples of how drawings brought out information that other methods had not revealed. Other researchers have investigated scientist stereotypes and also applied drawing methods to assess other attitudes, understandings, and affect (e.g. Flick, 1990; Mason, Kahle, & Gardner, 1991; Rosenthal, 1993; Schibeci & Sorensen, 1983; Thomas et al., 2001; Farland et al., 2011; Katz et al., 2013; Hillman et al., 2014). The authors in this volume carry the methods of using drawings in science education forward in the 21st century, finding a richness that words alone have not captured.

When we ask people to draw today we are asking them to engage in this act of creating a visual record. They agree to put their thoughts on paper, choosing sizes, spaces, symbols, shapes and sometimes colors. It is a different way of sharing knowledge from written language with its rules for meaningful sounds, sentence structure, syntax, spelling and other descriptive boundaries. It is just this set of rules that makes language work as cultural developments of distinctive speech. While there is evidence that drawing, as any human artifact, is also nested within a culture, we have seen that it can have the power to cross some boundaries, much as some sounds (pain, alarm, happy exclamations) transcend culture in their communication. With the increasing use of digital tools, visual imagery and graphic design (drawing, in this case) have the potential to increase democratization of observation and communication as images

jump across the internet internationally. This book focuses on handmade drawings using paper, pencil, crayon or inks. The eye, mind, hand coordination that drawing requires supports science learning. As Mensah and Fleshman suggest, drawing can be used to revisit memories and consider them from a different perspective, perhaps reinforcing a positive attitude toward self in science education (Chapter 19).

It is interesting to note that drawings in the name of science have been a part of major controversies. Our very sense of who we are has changed as science tools and culture allowed for world views that were illustrated first with the earth and then with the sun as the center of our collection of planets. As Gary Wind points out in his chapter (6) on medical illustration, teachable knowledge of the human body was delayed for centuries by the prohibition against human dissection and the drawings and notes that accompanied this anatomical data when access was permitted. Thus healing methods that depended on the recording of images that could be taught to medical personnel from one generation to another could not happen. When allowed, compendiums such as Gray's Anatomy (Standing, Ed. 1858/2015) became essential medical basics, as did Dr. Wind's own work as the author of texts on the vascular system (Wind & Valentine, 2013). While this is a dramatic example of the impact of drawing (or the lack thereof) it is the drawings that our predecessors left us that provide evidence of not only the flora and fauna in recent earth history, but to varying degrees, how our ancestors thought of themselves in it.

Given that drawing was an early and continuous means of providing data in science, I found it odd that teaching and research books such as *Taking Science to School* (NRC, 2007), the *Handbook of Qualitative Research* (2000), or the *Handbook of Research on Science Education* (2013), have no index heading for "drawing" as a method for teaching, learning and research. The latter does have a heading for "draw-a-scientist test." In this book, the authors use drawings as central evidence to gain insights into the thinking of participants in a broad range of cultures, settings, and stages of life.

There were options for how this book could be organized. Hope (2005) looked at children's design drawings and classified them as picture, single-draw, and multi-draw prior to children's use of drawings for idea development. Focusing then on the process of using drawings for design, she classified children's drawings into multi-draw, progressive and interactive, depending on how the child approached design development before construction. Ainsworth, Prain and Tytler (2011) considered the rationale for drawing as a critical skill and classified these as (1) Drawing to enhance engagement; (2) Drawing to learn to represent in science; (3) Drawing to reason; (4) Drawing as a learning strategy (5) Drawing to communicate. My own choice was historical. I find that a developmental approach helps to establish the building blocks of a field, providing the same history that we seek when we do a literature review to situate new knowledge. The chapters in this book are grouped into four sections that follow the ways in which the use of drawings has evolved and can still be in practice for science education. I made this decision because I hope that the book will be useful to practitioners as well as researchers.

Drawing then, is the oldest form of intentional human communication to transcend time. People were creating drawings before alphabets or pictograms were put down on stone, clay, or papyrus to leave records for the future. Drawings were used before alphabets symbolized sounds that had combinations for meaning. Drawings were useful before, perhaps, language was standardized. Drawing is thus a communication tool that we developed early in our human history. It is important. And yet, as Anning noted (1999), "At school, children quickly learn that drawing has low status," (p. 171) and it more often concentrates on adapting to certain practices. This book then, is about how drawing complements the written and the spoken. It is about how necessary this is in the varied ways people have chosen to use the process of drawing in science teaching and research—teaching about how the world works. It relates how, across cultures, those who draw are given a way to express what they are thinking that can be more open than verbal/literary responses. It is a book of examples that others may adapt. The following are brief descriptions of the material.

SECTION ONE—A SINGLE IMAGE

In an effort to attract more women as well as those who might not register for a university introductory physics course, Jatila Vanderveen describes how she incorporates visual thinking into her curriculum for her course on Symmetry and Aesthetics in Contemporary Physics at the University of California at Santa Barbara (UCSB). She begins by asking students to draw their understanding of Einstein's 1936 essay, *Physics and Reality*. Her chapter describes her analysis of visualization styles and her measurements of accomplishment.

Miri Barak explored the role of information and communication technologies (ICT's) at the Technion in Israel by prompting a sample of science and engineering undergraduates to "draw a learning situation in higher education" and requesting written explanations as well. From the drawing evidence, she considers the difference between the instructional culture of academia and the alternative learning strategies revealed in her study, finding a considerable distance between the two.

In working with pre-service middle and secondary level teachers, Patricia Patrick sought insights into the social contexts in which these teacher candidates learned about anatomy. The drawings served as discussion objects between participants who first drew the anatomical systems in both a human and a pig (as closely related). Prior research had indicated that anatomical drawings of humans concentrate on the gastrointestinal and cardiovascular systems without investigating the source of this information. This study explored the potential for shared cultural conceptions and misconceptions as that source.

Amauri Bartoszeck and Sue Dale Tunnicliffe collected hundreds of drawings by students in four studies within this chapter. The illustrators ranged upwards from four years old and came from rural settings, towns, and suburban areas in Brazil where these researchers

explored children's general levels of understanding of organisms, both plant and animal. They find that drawing is a useful tool to access mental models. This trend data confirms the ability of children to represent increasing detail in their observations and representations.

Gary Wind, a teaching physician at the U.S. Uniformed Services University of the Health Sciences, has contributed an essay on the history of medicine's reliance on drawing. He describes early anatomical illustration as it developed into a critical teaching tool for the healing arts. Dr. Wind has been an eager medical artist himself, speaking to his first interest in cartooning as it grew alongside his interest in anatomy. In high school, he became aware of Vesalius' work, setting him on the path to his own work as a microvascular practitioner and teacher.

In exploring children's concepts of nature, Amy Dai asked children entering formal schooling in Taiwan to draw their ideas about nature. Most children live in densely populated areas where the original (natural) environment has been altered for human habitation. From this study, Dr. Dai concluded that children and teachers would benefit from planned green spaces for direct observation of the interrelationship of plants, animals and humans. She also notes that children come to school with prior knowledge, both positive and negative, in their "nature" concepts.

Working in Bangladesh with rural women who had not had the opportunity to advance their formal schooling, Sue Dale Tunnicliffe and Angshuman Sarker investigated anatomical knowledge. The women were provided with a body outline to draw their internal organs. They were also asked where they had learned about their bodies. The researchers were surprised to find some well-placed knowledge of kidneys, unlike comparable Western data. Taking advantage of children's presence, drawings also revealed that schooling did yield more anatomical information.

SECTION TWO—MULTIPLE DRAWINGS TO EXPLORE CHANGE

Pre and post drawings of a marine environment enabled Jill Caine, Lauren Humphrey and Rob Bowker to assess learning in two settings. In the UK's Plymouth Aquarium, children's drawings showed increased mastery of detailed observation. In an adult training program aimed at the connection between reef conservation and the economy in Mauritius, the researchers found that the training program met its learning goals for low-income ESL workers. They found that using drawings enabled feedback independent of language and initial educational skills.

In considering the prior conceptions that students bring to their school science studies, Susanne Neumann and Martin Hopf discuss research on the terms "energy" and "chemistry." They also had an unusual opportunity to conduct research among Austrian students (age 9–12), about the concept of "radiation" before and two years after the Fukushima accident in Japan (2011). They suggest that among this young age group, the international media coverage and ensuing discussions resulted in a doubling of drawn motifs related to radioactivity.

Katrina Rosseler and Michael Dentzau analyzed drawings through the contextual model of learning to investigate informal science education. Pre and post drawings after a series of visits to the E.O. Wilson Biophilia Center in Florida provided data within the model's categories of personal, sociocultural and physical contexts as they combine over time. There is clear evidence that the Center visit enhanced the understanding of the longleaf pine forest for fourth graders. In other research, they asked undergraduates to draw and annotate an image of themselves participating in science outside of schools, gaining insights into informal science experiences.

Working with young children, Ni Chang argues for visual teaching and learning alongside the traditional emphasis on reading and writing. In this integrated curriculum, she finds power for children who enter a multimedia world, cautioning that teachers must state clear learning purposes for drawing. This chapter describes the findings of 70 pre-service teachers who worked with 140 children (4–7 years old) through four semesters in a Midwest American university teacher preparation program utilizing pre-post instruction drawings for comparison.

In the multi-lingual context of South Africa, Michelle Stears and Edith R. Dempster found that drawings helped to remove the distinction between affluent and poorer schools that text-based assessments highlighted. They investigated the growth of information about internal anatomy between first (7 year olds) and ninth graders (15 year olds). They concurred with other studies that children's awareness grows from what they can feel (bones and beating heart) to that of organs and systems and suggest a teaching sequence that integrates systems thinking.

At two science centers in Australia, Terence McClafferty and Leonie Rennie sought to gain insights into how visitors used interactive exhibits meant to teach the physics of sound and what they learned. To focus the visitors' illustrations, they presented partially drawn diagrams to complete and thereby convey an understanding of the exhibits' scientific concepts. They found that this method was efficient for the science center setting where visitors would find it easier to draw what they understood, rather than verbally describe it. Half of the study participants provided evidence that visitors learned something new, with females and younger visitors in the lead.

SECTION THREE—DRAWINGS THAT ILLUSTRATE THE PERCEIVED CULTURE OF SCIENCE

Donna Farland-Smith writes of her work refining the Draw-A-Scientist Test (DAST) developed by Chambers in 1983. For nearly 30 years, the test was used to make claims about stereotypical images of the who, what, and where of science. Countering the controversy surrounding this "test," in terms of its validity and reliability, she collaborated in the development of a modified protocol and rubric

in 2013 to standardize data collection in her work in the USA. The modification included multiple drawings by the same illustrator. Farland-Smith asserts that these drawings reveal rich data with both cultural clues and representations of personal identities.

Noting some of the limitations of the DAST-C (Draw-A-Scientist Checklist), Sulaiman Al-Balushi and Abdullah Ambusaidi explored the beliefs of their prospective science teachers at Sultan Qaboos University in Oman. They found that their students represented a teacher-centered classroom although observations in practicum situations did include a wider variety of methods, leading to suggestions for DAST development to include analysis of practice as well as beliefs. They conclude that further research on combined drawing and interviewing would be helpful.

In Turkey, Sinan Ozgelen gave third grade students the option to draw images along with open-ended survey questions when he asked what science was, who did it, and how it was done. He was thus able to collect data on student preferences for written responses, drawn responses or a combination of both. The influence of Turkish curricular textbooks is considered and compared to other drawing data in light of recent reforms, with notable differences credited to the way in which scientists are presented in the country's newer material.

Seeking to understand the meanings that learners construct around science, Jeremy Price asked high school students from a diverse middle track class in the northeastern USA to draw a picture and reflect about (in writing and discussions) what doing science looks like to them. He repeated the procedure early and at the end of a two month period of collaboration with the teacher and class. The drawings aided analysis of the students' current concepts of where science is done, with what equipment, knowledge and concept development, who is involved and how.

SECTION FOUR—DRAWING FOR AND ABOUT SCIENCE TEACHER IDENTITY DEVELOPMENT

Felicia Moore Mensah and Robin Fleshman use drawings and narrative with their pre-service teachers in the USA to help their students revisit their past conceptions and rethink their emerging new science teacher identities. Their procedure, DESTIN (Drawing-Elementary-Science-Teacher-Not) uniquely analyzes diversity as it is examined in multicultural education. Drawings are thus not only a source of student images, but a proactive tool to construct thoughtful and positive representations as students learn during teacher preparation.

In Botswana, the term "inclusion" is evolving from a focus on disabilities, to a term that connotes the effort to teach students who are at risk of failure to reach their maximum potential. Shiellah Keletso has written a personal narrative as a teacher-researcher, using drawings to gather information of her students' perception of her teaching. She used this information to change her own teaching behaviors to better communicate with her students and provide a learning environment to encourage them to succeed. She found inspiration on the Project Nexus website at the University of Maryland.

Randy McGinnis and Emily Hestness (USA) explored prospective elementary teachers' perspectives on climate change, seeking insights into their moral reasoning on this socioscientific issue. Combined with narratives, they used drawings as a way to elicit information in a creative and non-threatening way, with a prompt that asked for all that a student knew about the causes and effects of climate change. They consider how prospective teachers must contemplate the personal and societal responsibility of issues in light of the rational emphasis that is common in science.

New Zealand teacher educators David Winter and Chris Astall extended the use of drawings through the addition of video narratives to create learning monographs among a small group of students enrolled in a postgraduate education qualification. In repeated drawing opportunities, a sample of volunteer students spoke to a video camera describing and explaining what they had drawn. Not only do the students clarify and provide additional thoughts, but this method gives them the opportunity to engage in self-reflection through observing their own work.

Taken together, these chapters present a variety of ways in which drawing helps not only teacher/researchers learn what their students or audience already know, or what they take from a teaching setting, but how the illustrators may see themselves in the process of learning science. As I read these chapters, I became more concerned that drawing, unlike reading, is not front and center in science education. Participating in constructing mental images to communicate is part of our heritage. Observing the world (and oneself in it) and expressing one's thoughts by organizing and producing images are useful to illustrator and researcher alike.

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Phyllis Katz

University of Maryland, USA

SECTION ONE

DRAWING A SINGLE IMAGE

2. DRAW YOUR PHYSICS HOMEWORK?

Art as a Path to Understanding and Assessment in Undergraduate Science Education

INTRODUCTION: ARTS-BASED TEACHING- A PATH TOWARD INCREASING DIVERSITY IN PHYSICS?

In spite of government initiatives to attract a more diverse population of learners into science and technology, results of a number of studies in the United States (Hazari et al., 2010; Blickenstaff, 2005, e.g.) and Europe (Sjøberg & Schreiner, 2007, e.g.) suggest that the standard introductory physics curriculum – the gateway course for all science and technology majors – may be a deterrent for many students, particularly females. Thus, my initial motivation for incorporating arts-based teaching strategies in an introductory physics course was an attempt to redress the persistent gender bias in physics by attracting a broader population of learners *in general*, which would naturally include females. After eight years of teaching this course, I can report that, although it remains a small-sized elective, 41% of the students who have completed my course are female – slightly more than double the most recent count of the percentage of women earning bachelors degrees in physics (<http://www.aps.org/programs/education/statistics/womenstem.cfm>, 2015). The evaluations remain consistently high, with many students reporting in their anonymous exit comments that they would not have taken physics in college if not for this class, and several physics majors reporting that this course renewed their interest in pursuing a physics degree.

The separation of arts and sciences has been ingrained in Western society at least since the 17th century, and has been embedded in American education since the 19th century (Eisner, 2002). Eisner attributes the cultural dominance of science over the arts to the Enlightenment in Western society, which was heavily influenced by the emergence of Newtonian physics:

Science was considered dependable; the artistic process was not. Science was cognitive; the arts were emotional. Science was teachable; the arts required talent. Science was testable; the arts were matters of preference. Science was useful; the arts were ornamental. It was clear to many then, as it is to many today, which side of the coin mattered. (Eisner, 2002, p. 6)

In spite of this separation in education, *people* are not so compartmentalized in their ways of thinking, and many scientists pursue serious recreational or semi-professional endeavors in the arts. Historically, there is a likely correlation between explorations in music and discoveries in physics (Pesic, 2014). In my own life in physics and dance, I have noticed a great many people, both men and women, whom I meet at serious amateur recreational dance events (folk dance, contra dance, and ballroom competitions) have jobs in science or technology, and I know a surprising number of other semi-professional dancers (like myself) who have Ph.D.'s in science, engineering, or medicine. An email survey I sent to three international recreational dance mailing lists revealed that no fewer than 60% of respondents who dance have jobs in physics, engineering, or computer science (van der Veen, 2006). According to the U.S. Census for the year 2000, only 27% of middle-income urban populations held jobs in STEM fields, including architecture. The recent movement towards “turning STEM to STEAM” in K-12 and colleges in many states is evidence that educators, artists, and scientists are beginning to reach across the divide.

My research on arts-based teaching strategies in introductory physics is intertwined with my work on restructuring the introductory physics curriculum. In my undergraduate seminar, *Symmetry and Aesthetics in Contemporary Physics*, we explore Symmetry as the mathematical foundation of physics as well as the conceptual link between physics and the arts. We trace the development of symmetry and group theory from their origins in pure mathematics to their various manifestations in the phenomenological universe, and investigate how contemporary ideas of spacetime evolved from the discovery of broken symmetries in the late nineteenth and early twentieth centuries in classical mechanics, electromagnetic theory, and the discovery of the speed of light. Throughout the course we use drawing and other artistic representations to explore, explain, and comment upon mathematics and contemporary physics.

Symmetry in physics refers to the concept of ‘sameness within change,’ and is the basis of all the laws of physics. Symmetry is the set of rules that allow us to define the invariance of a system under rotations, reflections, and translations. Historically, when physicists have confronted an apparent paradox, it has been resolved by finding the symmetry that explains away the paradox by a change of coordinates (perspective). Thus, the search for deeper symmetries in Nature propels advancements in contemporary physics. Symmetry is also an important concept in human perception, biology, evolution, neuroscience, and chemistry. Symmetry and asymmetry are central to our aesthetic experiences in the arts, and thus provide a natural foundation for an interdisciplinary physics course that incorporates arts-based teaching strategies.

I start with contemporary physics as being more interesting and relevant to the lives of 21st century youth than classical Newtonian mechanics (Levrini, 1999), and treat math and the arts as complimentary semiotic systems for interrogating the physical universe (van der Veen, 2007, 2012, 2013). Teaching beginning students about Relativity and curved spacetime brings them face to face with some

of the ontological questions that motivate contemporary physics at the largest scales. Moreover, teaching about Relativity in its historic context provides the iconic example of how symmetry has come to play a fundamental role in the development of contemporary physics. It also brings to the fore Professor Emmy Noether, whose theorems on the relationship between continuous symmetries in nature and conservation laws in physics have played a seminal, yet little known, role in the development of new physical theories, and thus foregrounds the discrimination that women in physics have faced historically, and continue to face.

The seminal question motivating my research is: Can we use the arts to bring more people into a healthy dialog with physics, thus potentially increasing the diversity of learners who choose to study physics, whether to become scientists, engineers, teachers, or as part of a contemporary education? From this starting point, several results have emerged which have implications for physics education as well as education in general, regarding drawing and other arts-based approaches in curriculum design and assessment, including:

- Having students draw their understanding of an article, concept, or equation allows students to get in touch with their own visualization and thinking styles, and provides instructors insight into the kinds of thinkers their students are, so as to design curricula appropriately;
- Having students design their own artistic representations of science concepts at the undergraduate level allows them a form of expression through which to develop their own voices in math and physics, and thus deepen their personal connection with these often impersonal subjects;
- Having students design their own representations of math and physics concepts provides instructors with an alternate, in many ways deeper and more comprehensive, assessment of their understanding;
- Incorporating arts-based teaching strategies at the undergraduate level, especially in intimidating subjects such as physics, has the potential to increase interest in the subject for students who may otherwise have avoided physics.

DRAWING AS A MEANS FOR STUDENTS TO GET IN TOUCH WITH THEIR OWN VISUALIZATION AND THINKING STYLES

In my work with college students, I have found that drawing is a means by which a learner (artist) can get in touch with and express her or his own inner language and visualization style, and understand how he or she goes about the internal process of making sense of externally received information. Swiss educator Johann Heinrich Pestalozzi (1746–1827) was the first to propose the idea of the *Anschauung*: mental imagery developed by abstraction from phenomena that have been directly experienced (Pestalozzi, 1805/1894). Pestalozzi advocated a threefold system of interrogating the world: visualization, numeration, and description, or what he called form, number, and language. For successful education, these three aspects of making sense and creating meaning out of the physical world cannot be separated (Pestalozzi, 1805/1894). Einstein himself was trained in this method of *Anschauung* at the Kantonsschule at Arrau (Miller, 1989).

Mathematician Jacques Hadamard studied thinking processes among mathematicians and scientists in the first half of the 20th century, and found a widespread reliance on visual thinking. In a frequently-quoted letter to Hadamard as part of this study, Einstein wrote:

The words or the language, as they are written or spoken, do not seem to play any role in my mechanisms of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be voluntarily reproduced or combined.... this combinatory play seems to be the essential feature in productive thought before there is any connection with logical construction in words or other kinds of signs which can be communicated to others. (Hadamard, 1945/1954, p. 142)

In training students to think like scientists, the use of drawing and other arts-based representations, both student generated original representations and the study of professional artists' representations of physics concepts, should be an integral part of our science and math curriculum. The importance of visualization in scientific thought and discovery cannot be overstated, yet most early physics training at the undergraduate level relies exclusively on problem solving and the interpretation of graphs.

Some students visualize mathematical relationships quite easily, as reported by this first-year male physics student in 2007:

I think of calculus, differentials, and many other things visually. I am so entrenched in math that I use rudimentary forms of 'visual calculus' even when I play games. To imagine a curve of a damped oscillator is as intimately connected with a spring as the word 'apple' is to holding one in your hand.

For others, visualizing and translating their mental images into a physical representation is more difficult, as reported by a female political science major in 2011:

It is definitely very difficult to translate my mental image from my mind through a pen and onto paper. Although they are formed by me in my head, I almost can't grasp exactly how it appears to me.

Nevertheless, by the end of my course all the students are able to create a representation of a concept which inspired them, through the artistic medium of their choice – drawing, painting, sculpture, computer graphics, literature, poetry, dance, music, or a combination of media. They are able to communicate their ideas through their physics works of art to each other as well as to a general public audience in a gallery showing of their final physics works of art. They leave with a sense of pride, accomplishment, and community.

To set the tone of the course, I begin by interrogating the process of physics and the role of mathematics as a language of nature. For the first art assignment I ask students to draw their visualizations of Einstein's description of the nature of physics in his article *Physics and Reality*. Although Einstein wrote this essay in 1936, it is still relevant today.

FIRST DRAWING ASSIGNMENT: REPRESENTING AN ARTICLE BY EINSTEIN ON THE NATURE OF SCIENCE

Einstein's highly visual thinking style is evident in his 1936 essay, *Physics and Reality*. I assign this article as the first reading assignment in my course, Symmetry and Aesthetics in Contemporary Physics, which I teach every year in the College of Creative Studies at the University of California, Santa Barbara. The foundational assumptions of western science as articulated by Einstein in this piece make it an excellent starting point for discussions on the Nature of Science, summarized in the following quotes:

1. "The whole of science is nothing more than a refinement of everyday thinking" (p. 23);
2. "One may say 'the eternal mystery of the world is its comprehensibility.' It is one of the great realizations of Immanuel Kant that the postulation of a real external world would be senseless without this comprehensibility" (pp. 23–24);
3. "The aim of science is, on the one hand, a comprehension, as complete as possible, of the connection between the sense experiences in their totality, and, on the other hand, the accomplishment of this aim by the use of a minimum of primary concepts and relations" (p. 24).

In Einstein's view, primary concepts are connected directly to sensory experiences but lack in "logical unity." They are then connected to each other through a secondary level of concepts, which has a higher degree of logical unity, but is removed from direct sensory experience, and which is connected through successively higher layers until

we have arrived at a system of the greatest conceivable unity, and of the greatest poverty of concepts of the logical foundations, which is still compatible with the observations made by our senses. (p. 25)

The first art project I assign each year is for students to draw their understanding of this essay by Einstein. His visual writing style, coupled with my opinion that to understand the nature of science one must read the opinions of those who create and define the field, make this article an ideal starting point for introducing drawing as a means of understanding and sense-making in physics, especially in a course that seeks to create an oppositional identity to mainstream introductory physics.

Classifying Visualization Styles through Students' Drawings

Over the eight years I have taught this course I have observed that students' drawings fall into certain rather clear categories, suggesting that visualization style is a characteristic that reveals the way in which an individual makes internal sense out of the external world – a *language of the mind* (John-Steiner, 1997).

Previous studies have looked at the binary classification of visual and verbal learners, while others have further classified visual learners either spatially-oriented or object-oriented. According to Kozhevnikov, Kosslyn, and Shepphard (2005), object-oriented visualizers process images holistically, as a unit, while spatially-oriented visualizers process images analytically, part by part. Results of their study suggest that scientists and engineers tend to be spatially-oriented visualizers who have an easier time recalling processes, while artists tend to be object-oriented visualizers who have an easier time recalling static images as a whole. Other studies have claimed that males tend to be spatial visualizers while females tend to be object-oriented visualizers. The results of Kozhevnikov et al. (2005) suggest that there is no clear correlation between biological gender and either spatial visualization strategy or ability to solve abstract mathematical problems. A number of studies suggest that males tend to perform better than females on a variety of spatial orientation and mental rotation tasks (Collins & Kimura, 1997; Geary & Soto, 2001, e.g.). Hegarty and Kozhevnikov (1999) found that visual-spatial representations used by elementary school children while solving mathematical problems can be reliably classified as primarily schematic, associated with understanding spatial relationships from multiple perspectives, or primarily pictorial and object oriented. Moreover, they found that the use of primarily schematic spatial representations was positively correlated with success in mathematical problem solving, while the use of primarily pictorial representations was negatively correlated with success in math but positively correlated with success in art (p. 51). On the other hand, studies of visual imagery by Campos, Gomez-Juncal, and Perez-Fabello (2007) suggest that it is experience, rather than gender, which dictates a student's competence at generating mental images, and that the ability to produce vivid mental images is a learned skill that can be enhanced through instruction and practice.

When I began analyzing my students' drawings, I was curious to see whether the drawing styles of physics majors, biology majors, arts majors, and humanities majors would have any distinguishing recognizable characteristics, and whether the drawing styles of biological males and females would be different. I find that elements of spatial, temporal, and part-by-part visualizations, as well as holistic, at-a-glance types of drawings described in previous studies do not follow boundaries of gender or major in college. Rather, I observe six general categories of visualization styles, which emerged after four years of collecting students' drawings of their interpretation of the Einstein article. In the spirit of Grounded Theory, in which theory emerges from data, I developed a means of coding students' drawings based on general characteristics I found in their representations from year to year:

1. the type of symbols used: abstract or pictorial;
2. the type of representation: direct mapping of concept in the article to symbol in the picture or representation of the article as a whole by a pictorial analogy or metaphor;
3. the representation of some sort of temporal progression;
4. the representation of the article as a whole with an allegory or “what if” scenario (van der Veen, 2012).

Based on these characteristics, I named six categories of visualization style: *direct-symbolic*, *abstract-representational*, *metaphoric/analogical*, *allegorical-creative*, *flow chart*, and *hybrid* (van der Veen, 2012). After eight years, these categories remain. Moreover, certain themes within the general visualization styles have begun to repeat themselves.

Direct-symbolic drawings utilize recognizable objects or symbols to represent concepts in the article in a literal, one-to-one mapping of symbol to concept, sometimes with arrows drawn to indicate correspondences, or with labels placed directly on the drawing. Some drawings depict the hierarchy of concepts with a pyramid, while others use examples of what students consider to be a hierarchical ordering of concepts (microscopes to telescopes, e.g.), but all are more-or-less literal interpretations of the article (Figures 1–4).

Abstract-representational drawings are also literal interpretations of the article, but use abstract symbols with a one-to-one correspondence between the symbol in the drawing and the concept in the article instead of recognizable objects. No labels are included directly on the drawing, but the direct, one-to-one correspondence between symbol in the drawing and concept in the article is described by the student in the written or verbal description of his/her drawing (Figures 7 and 8).

Metaphoric/analogical drawings use a metaphor or analogy to represent the article as a whole with a single vision, almost a poetic painting that captures what the student artist senses as the gestalt of the article (Figures 9–11).

Allegorical-creative drawings represent the article as a whole with a pictorial story (allegory or ‘what if’ scenario) that seems to begin where the article leaves off (Figure 12).

Flow charts incorporate some element of temporal progression using arrows to indicate the sequential nature of science or the flow of concepts. The drawings I have classified as flow charts utilize a range of symbols connected by arrows to represent the flow of ideas in the article, from completely pictorial to completely verbal (Figure 13).

Hybrid drawings do not appear to fit squarely into a single category, but embody elements of two or more categories, such as direct-symbolic and allegorical (Figures 5a and 5b), direct-symbolic and metaphoric-analogical (Figure 6), and flow chart and metaphoric-analogical (Figure 14).

After four years of giving the same initial drawing assignment, I noticed these patterns and named them. I searched for a theoretical model through which to build a case for a relationship between students’ preferred visualization styles and their preferred learning styles, and found Felder and Silverman’s (1988) model of learning preferences of engineering students (Felder & Silverman, 1988; Felder, 1993). In their original model, Felder and Silverman describe five opposing traits which, in varying proportions, describe students’ learning preferences: sensory vs. intuitive, visual vs. verbal, inductive vs. deductive, active vs. reflective, and sequential vs. global. I looked for a correlation between the visualization styles I found in my students’ drawings and Felder and Silverman’s learning preferences model (van der Veen, 2012). However, after eight years of giving the same initial drawing assignment, I feel that it is more appropriate to interpret these visualization styles as “languages of the mind” (John-Steiner, 1997) rather than constrain them by any specific cognitive-behavioral descriptions, as students who draw the same type of visualization do not necessarily fit into similar learning patterns. Rather, students’ preferred visualization styles are a kind of window into their minds, providing insights into their backgrounds, the experiences they bring to the study of physics, their prejudices and personal philosophies, as well as how they process information. In a very real sense, students’ drawings in an undergraduate physics seminar reveal the literacy narratives they bring with them (Kendrick & McKay, 2010), and use to make sense out of their study of physics.

I use this first drawing assignment not only to set the tone of using drawing as a means of sense-making and communication in physics, but also to encourage students to find their individual ‘visualization voices,’ and understand their own internal ways of knowing and sense making. My students continue to develop their representational competence in three more arts-based assignments throughout the course, culminating in their final physics works of art. The final projects are displayed in one of the campus art galleries, with a public reception in which the students must explain the concept(s) they have chosen to represent to an audience of peers, faculty and staff, and members of the public (see, for example: <http://www.news.ucsb.edu/2015/015237/art-physics>).

Below I present examples of the six types of visualization categories that have emerged from the first art assignment, “Draw your understanding of Einstein’s article, *Physics and Reality*.”

Direct Symbolic Representations

The unifying feature of direct-symbolic drawings is the one-to-one mapping of symbol in the drawing to concept in the article, often with labels written directly on the drawing. Some students choose to represent the *process* of doing science described by Einstein as a linear progression, while others choose to represent the *hierarchy of concepts*, but in either case there is no ambiguity as to the

correspondence between symbols in the drawing statements in the article. Examples of direct-symbolic drawings by a literature major, a political science major, an art major, and a religious studies major are shown in Figures 1, 2, 3, and 4, respectively. I have chosen these examples because they are all direct symbolic drawings, but also display a range of interpretations by students who have had limited or no prior exposure to physics.

Figure 1 was drawn by a literature major, who stated that she would have been more comfortable doing a literary interpretation, such as a poem (which she did for her final project), than a drawing:

In this essay, Einstein discusses the limits of human knowledge. He describes a subjective reality which is built on the framework of “sense perceptions” tied together by logical deductions. Einstein then describes an ontological hierarchy, a pyramid of sorts, in which primary concepts and statements of reality are narrowed down until we are left with the point of the pyramid, which is the essence of reality.

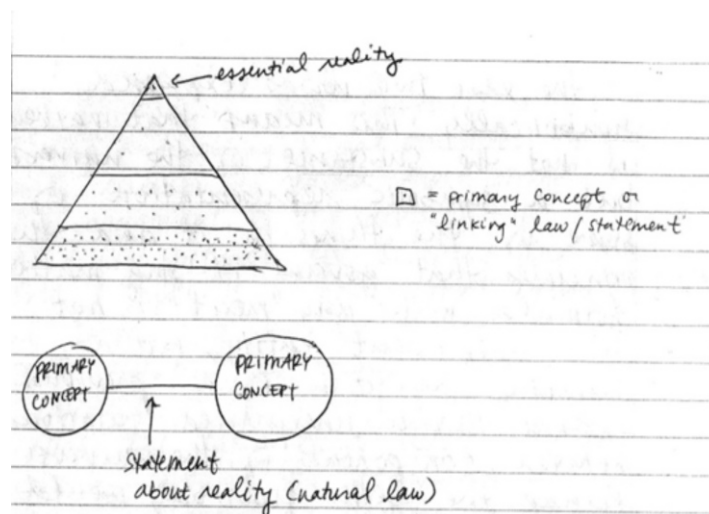


Figure 1. Direct symbolic representation. Female literature major, 2007 (Van der Veen, 2007,2012)

Figure 2, drawn by a female political science major, depicts the process of doing science as linear, starting from external events which are taken in by the senses to form an internalized concept of reality, represented by an array of mathematical and musical symbols, depicted in no particular order.

The ability to construct a reality or external world comes from the associations we make between our sensory inputs and our concept of bodily objects. Our minds give significance to these concepts and the relations between different concepts allow us to connect sense expressions and create a “reality.” This translates into comprehensibility which is the production of some sort of order among sense impressions.

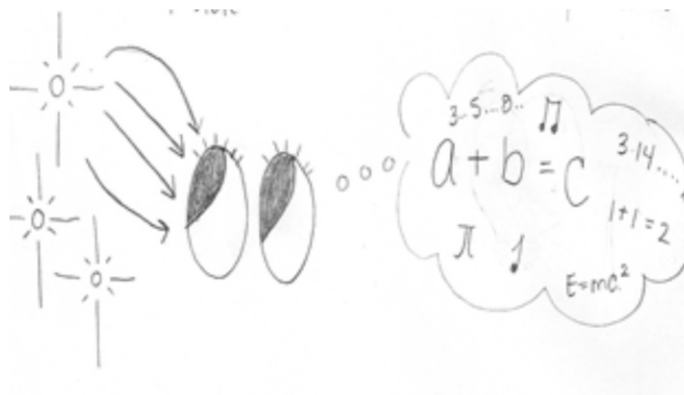


Figure 2. Direct symbolic drawing. Female political science major, 2011

Figure 3 was drawn by a third year female art major. I classify it as direct symbolic because of her use of labels on the drawing.

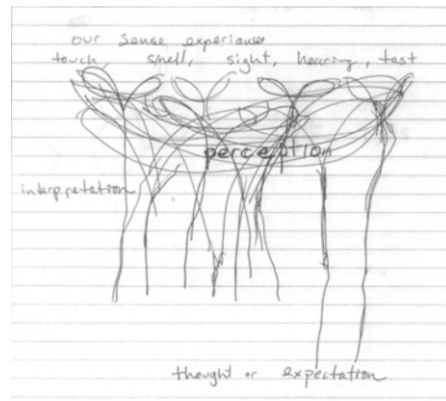


Figure 3. Direct symbolic drawing. 3rd year female art major, 2007

In her brief description she referred only to statements made by Einstein in the first two pages of the article:

Einstein is saying that a physicist must start to philosophize because the foundation of our experience is shifty. Because science is thinking, it is then natural to examine the process of thought.

Her interpretation of Einstein's culmination of the layers of sensory input and theory leading to the "greatest conceivable unity" of concepts as merely "thought or expectation" could represent the fact that she did not complete the reading assignment, but did not want to come to class empty-handed, or perhaps I should have recognized her drawing as a sign that she was going to need extra help. Throughout most of the course she expressed an intense mistrust of physics and physicists, including physicists' use of language and their emphasis on theory over sensory perception. Her frustration reached its peak expression in her literary argument with Nobel Laureate Richard Feynman's description of the surface of a cylinder as a flat space (Feynman, 1963):

...when it comes to a cylinder whose space seems to be obviously curved we find it does not have curved space because Euclidian geometry holds. My first reaction is to say that the definition that Feynman gave in the beginning must be wrong because a cylinder is obviously curved to an outside perspective despite not having intrinsic curvature.

She continued with her verbal confrontations about this issue with me, with the physics majors in the class, and after class with a post-doctoral scholar with whom I shared an office at that time. By the end of the course, though, she reversed her opinion, and wrote in her final evaluation:

I found this course to be wonderfully exciting. The instructor and the students were wonderful and passionate, which made the class a pleasure. I had to overcome and grapple with a lot of struggles with math and understanding the language of science. I wish that this class would continue and I could continue to study the math and science in such an integrated way.

Figure 4 was drawn by a third year male religious studies major. I classified his drawing as direct symbolic because he lists his legend in the upper left, and uses labels and arrows to indicate the correspondance of symbols in his drawing to his legend.



Figure 4. Direct symbolic. 3rd year male religious studies major, 2014