

Development and Analysis of New 3D Tactile Materials for the Enhancement of STEM
Education for the Blind and Visually Impaired

by
Ashleigh Gonzales

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Graduate Supervisory Committee:

Debra Page Baluch, Chair
Karin Ellison
Jane Maienschein

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ABSTRACT

Blind and visually impaired individuals have historically demonstrated a low participation in the fields of science, engineering, mathematics, and technology (STEM). This low participation is reflected in both their education and career choices. Despite the establishment of the Americans with Disabilities Act (ADA) and the Individuals with Disabilities Education Act (IDEA), blind and visually impaired (BVI) students continue to academically fall below the level of their sighted peers in the areas of science and math. Although this deficit is created by many factors, this study focuses on the lack of adequate accessible image based instructional materials. Traditional methods for creating accessible image materials for the vision impaired have included detailed verbal descriptions accompanying an image or conversion into a simplified tactile graphic. It is very common that no substitute materials will be provided to students within STEM courses because they are image rich disciplines and often include a large number images, diagrams and charts. Additionally, images that are translated into text or simplified into basic line drawings are frequently inadequate because they rely on the interpretations of resource personnel who do not have expertise in STEM. Within this study, a method to create a new type of tactile 3D image was developed using High Density Polyethylene (HDPE) and Computer Numeric Control (CNC) milling. These tactile image boards preserve high levels of detail when compared to the original print image. To determine the discernibility and effectiveness of tactile images, these customizable boards were tested in various

university classrooms as well as in participation studies which included BVI and sighted students. Results from these studies indicate that tactile images are discernable and were found to improve performance in lab exercises as much as 60% for those with visual impairment. Incorporating tactile HDPE 3D images into a classroom setting was shown to increase the interest, participation and performance of BVI students suggesting that this type of 3D tactile image should be incorporated into STEM classes to increase the participation of these students and improve the level of training they receive in science and math.

DEDICATION

I dedicate this research to my wonderful parents who have always shown me support and guidance. Thank you for always encouraging me to achieve my dreams despite seemingly insurmountable hurdles of life. I also dedicate this work to my siblings and close friends. Thank you for encouraging me and reminding me that work can also be fun. Finally, this work is dedicated to individuals with disabilities who seek to reach goals beyond the expectations of others. Thank you for being an inspiration to me and for motivating my work.

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Chapter 1. Laws Protecting Individuals with Disabilities

Studying and working in the fields of Science, Technology, Engineering, and Mathematics (STEM) typically requires that one have access to a variety of images, diagrams, figures, and other visual elements. This reliance on graphic components makes STEM subjects difficult for blind and visually impaired (VI) individuals to pursue. There is an average of 21.5 million blind or VI people in the United States (American Foundation for the Blind, 2014). Studies have shown that by the age of 16, most blind or VI individuals are an average of three years behind their peers in STEM subjects (Wagner, et al., 2003). This data supports the fact that less than five percent of people that work in STEM careers have a visual impairment. It is not clear why these students are so far behind in STEM subjects so early in their academic careers. However, it seems highly likely that a high dependence on visual elements in various STEM fields coupled with the lack of accessible images is partially responsible for this deficit.

Creating an Accessible Classroom

The research that follows demonstrates several possible issues that may be contributing to the low number of blind and VI STEM participants. As mentioned previously, a heavy emphasis on visual components in the majority of STEM subjects is one of the largest explanations to why there is reduced participation by the blind and VI. Access to effective tactile graphics, tools, and models is scarce and even non-existent in some academic institutions. According to Beck-Winchatz and Riccobono (2008), many blind students in science classes are often left without crucial classroom resources, including accessible graphics. Several research studies have been performed to identify

useful methods of conveying graphical information to blind and VI students. These studies involve the use of audio and computer resources to provide translation of the visual information (Levy & Lahav, 2012). However, it is frequently noted that the use of tactile and hands-on-materials is crucial to create a strong academic setting for these students (Janssen, et al., 2010). Many studies have provided suggestions to meet this need for tactile resources in STEM classrooms. These resources include braille labeling, tactile labeling, providing hands-on models, and providing tactile images (Kumar, et al., 2001; Supalo, 2005; Winograd & Rankel, 2007). Similarly, the research described in this report also described the development of a new type of tactile graphic. Despite these ideas, resources, and suggestions, blind and VI students continue to demonstrate low participation in STEM suggesting that the problem is more complex and should be investigated further.

There appears to be larger issues to consider when trying to determine why there is such a lack of blind and VI participation in STEM. One of the problems encountered is the lack of motivation on the part of schools and educators to spend extra time and resources on students with disabilities. According to Kumar et al. (2001), 38% of special education students receive little to no science instruction, most science instructors have no experience educating students with special needs, and schools often view additional resources for students with disabilities as too expensive. Furthermore, many accommodations that can make science accessible to blind and VI students are seen as too complex and overpriced (Beck-Winchatz & Riccobono, 2008). In addition to the generally assumed high cost of accessible education, there is a distinct lack of awareness on the part of schools and educators. That is to say, they are simply unaware of the types

of resources available to educate students with visual impairments. According to Supalo (2005), some of the difficult aspects of learning science for a blind or VI student are often neglected by their instructors. This means that although several resources already exist to assist visually impaired students, most educators do not take the time to look for them. This is quite a striking conclusion since there are current laws in place that are meant to prevent such situations.

ADA and IDEA

The American's with Disabilities Act (ADA) is a lengthy and descriptive set of laws that represents several years of hard work. The ADA consists of a detailed outline of the rights of people with disabilities living in the United States. According to the ADA law, the term "disability" means "a physical or mental impairment that substantially limits one or more major life activities of such individual; a record of such an impairment; or being regarded as having such an impairment" (ADA, 2008). The document also defines the rights of people who meet the definition of having a disability in several important venues including public transportation, employment, and of course education.

A Brief History

The ADA law represents nearly 20 years of hard work following its predecessor the Rehabilitation Act (Concannon, 2012). The Rehabilitation Act was a set of laws that went into effect in 1973 and was the first set of laws granting significant federal rights to persons with disabilities (Zink, 2004). The laws covered basic rights of people with disabilities, included plans for funding programs, and research plans to evaluate the

overall goals of the act (Buttons & Applequist, 2007). Government funding was allocated to different programs that would benefit people with disabilities. These programs included services to assist people with disabilities in areas such as finding employment, providing tools to help people with disabilities gain independence, and other similar services (Buttons & Applequist, 2007). The Rehabilitation Act also had sections which cover; 1) the employment of disabled people in federal government positions, 2) the removal of physical and architectural barriers to the disabled in federally funded buildings, 3) the protection of disabled people's rights when employed by any federal government contractor, and 4) protects the rights of disabled people receiving services from any group that receives federal financial assistance (Zink, 2004).

Since the scope of the Rehabilitation Act mainly covered the Federal government, a larger movement began to work towards a more comprehensive set of laws. The ADA was finally signed into law in 1990 (Figure 1), after much debate and discussion (Essex-Sorlie, 1994). Congress felt that the range of the Rehabilitation Act was not sufficient enough to fully protect the rights of those with disabilities. Thus the main differences between the Rehabilitation Act and the ADA, is that the ADA laws included protection for a much broader population (Leuchovius, et al., 2014). The ADA is essentially a reformatted and expanded version of its predecessor that includes provisions for the state and local governments as well as more detailed definitions and specificities than the Rehabilitation Act.

Contents of the ADA: Americans with Disabilities Act

The main body of the ADA law includes three titles. Each title covers laws and rights of people with disabilities with Title I dealing with employment of people with disabilities, Title II covering public services, and Title III discussing public accommodations and services provided by private entities (2008). There are a few other titles, however these three titles form the bulk of the laws (Americans with Disabilities Act, 2008). Title I, similar to the majority of the Rehabilitation Act, protects qualified individuals with disabilities from discrimination in terms of employment (Essex-Sorlie, 1994). It provides guidelines for employers to follow including the requirement to provide “reasonable accommodations” for employees with disabilities (The Americans with Disabilities Act, 2008). Title II of the ADA discusses rights for people with disabilities in regards to most forms of public services and public transportation including city busses and rails (ADA, 2008; Essex-Sorlie, 1994). Title III discusses laws for private entities that happen to provide public services such as stores and hotels (ADA, 2008). The other titles (not discussed here) cover telecommunications laws and a variety of other miscellaneous topics. The titles most relevant to the research involving accessible STEM education are Titles II and III.

Title II of the ADA discusses the laws that apply to public services, including public education. The general purpose of Title II is to state that people with disabilities must not be prevented from participating in or receiving any benefits from a public service (ADA, 2008). Title III of the ADA outlines important laws regarding public accommodations and services which are provided by private entities (ADA, 2008). The term “private entities” includes (among others): restaurants, hotels, theaters, museums, stores, and schools (ADA, 2008). Under this title, nursery, elementary, secondary, post-

secondary, and other schools are required to meet ADA standards by providing accommodations for students with disabilities (Essex-Sorlie, 1994). Together, Title II and III of the ADA provide basic rights and laws for people with disabilities in regards to education. Although these portions of the ADA represent a vital component of protecting the rights of students with disabilities, there is yet another set of important laws that apply to education.

IDEA: Individuals with Disabilities Education Act

Although the Rehabilitation Act and the ADA both provided laws and guidelines for ensuring an equal education for students with disabilities, they did not necessarily provide the resources to do so. In 1975, not long after the Rehabilitation Act went into effect, congress signed the Education for All Handicapped Children Act into law, introducing the concept of a “Free Appropriate Public Education” for all students with disabilities (“Education for All,” 2011). Among other provisions, the Education for All Handicapped Children Act requires parents and educators of children with disabilities to create and follow an individualized education program (IEP) to meet educational goals (2011).

In 1990, The Education for All Handicapped Children Act was amended and given a new title, The Individuals with Disabilities Education Act (IDEA, 2011). IDEA included several components of its predecessor as well as provisions for infants and toddlers with disabilities (IDEA, 2011). It also includes four separate parts that effectively provide support for educating students with disabilities. Part A is “General Provisions” and gives a general summary of the purpose of IDEA in addition to listing

several important definitions (Jones, 2002). Parts B and C, “Assistance for Education of All Children with Disabilities” and “Early Intervention Program for Infants and Toddlers with Disabilities”, each provide details about federal assistance and support for the groups being served (Jones, 2002). Part D is called “National Activities to Improve Education of Children with Disabilities” and explains the support provided by the federal government to assist with the implementation of Parts B and C (Jones, 2002). The act outlines sources of funding, including federal grants that can assist schools and communities so they can provide a free and appropriate public education to students with disabilities. In essence, the Rehabilitation and ADA provide the laws and requirements for providing equal education to students with disabilities, whereas IDEA provides the resources and funding to meet these requirements.

By the year 2000, the effects of IDEA and its predecessor were very apparent. The majority of students with disabilities were receiving equal and inclusive public education, the graduation rates of students with disabilities had increased by 14% in a 10 year span, and enrollment of students with disabilities in college tripled in a 20 year span (“History Twenty-Five Years,” 2000). IDEA was last amended in 2004, with most requirements going into effect by 2006. The major changes dealt mainly with provisions to the IEP and processes related to the IEP (“Individuals with Disabilities,” 2004). The amendments also required a new and higher standard for special education instructors (“Individuals with Disabilities,” 2004) however, the main goals and purpose of the original IDEA remained the same.

Difficulty Enforcing the ADA and IDEA

Despite the existence of a solid set of laws to protect people with disabilities in the United States and the added support of an education act to protect students with disabilities, there is still a long road ahead. Students are not always receiving the accommodations they need and have a right to. Others are not receiving the additional or specialized instruction they should be. Furthermore, students are often left out of activities their classmates are participating in due to a lack of accessible materials or an understanding of how to make an activity accessible. These issues have spawned a series of interesting and controversial lawsuits.

One of the very first lawsuits dealing with the ADA was filed by a college student. Nadelle Grantham was a deaf student in the elementary education program at Southeastern Louisiana University (SLU). In August of 1993, Grantham received a letter from the SLU expelling her from the elementary education program because they were concerned about her abilities to complete her courses and teach (“Deaf Student Wins,” 1996). After a series of court battles and appeals, Grantham was finally awarded \$180,000 for her case against SLU by the United States Court of Appeals for the Fifth Circuit in New Orleans (“Deaf Student Wins,” 1996). It was greatly due to the ADA laws that Grantham was able to successfully sue the University for discrimination. However, this case demonstrated that people with disabilities were facing an uphill battle in gaining compliance with the newly instated ADA laws.

A provision in the IDEA laws states that schools are obligated to identify and evaluate students they suspect have a disability. This is important because if a child with special needs is not identified, they will not receive the services they need to be

successful students. In 2002 a class action lawsuit began with *Jamie S. v. Milwaukee Public Schools*, for violations of the IDEA (Wright & Wright, 2012). A judge decided that the school district had violated IDEA laws by not accurately identifying and servicing students with special needs between 2000 and 2005. The court found that rather than properly evaluating students with behavioral and social problems, school employees often chose to simply suspend the students with no follow up (Wright & Wright, 2012). Milwaukee Public Schools tried to defend themselves by pointing out that the section of IDEA they had violated was only a small component, however the judge felt that identifying students with special needs was perhaps the most vital part of IDEA because it distinguishes which students are entitled to services (Wright & Wright, 2012). The school district was ordered to compensate the legal fees students and families acquired as a result of the lawsuit. Furthermore, a third party was brought in to evaluate the methods the schools used to identify and classify students who have special needs (Wright & Wright, 2012). It is clear that mandating compliance with ADA and IDEA requires vigilance and motivation of people with disabilities and those who face legal battles on their behalf.

Despite 24 years of ADA and IDEA implementation, lawsuits for violations of these acts have been filed as recently as 2011. A lawsuit was filed by two students at Florida State University for violations involving the use of inaccessible software and course materials. The students, both blind, stated that their math courses required the use of software for homework, tests, and studying, that was not accessible with screen reading software (“Blind Students Sue,” 2011). The students also sued the university because of its inefficiency in providing braille textbooks in a timely manner. The lawsuit

was settled out of court the following year with Florida State University agreeing to pay each student \$75,000 and to make a better effort to provide accessible materials to future students (“Florida State University,” 2012).

These cases, and many others, demonstrate that there is still something lacking in terms of proper implementation of the ADA and IDEA laws. Despite more than two decades of these acts being in place, there continues to be examples of difficulties faced by students with disabilities. If the barriers to these students aren’t fully addressed, there is the risk that they are not gaining the access to an equal education that they are entitled to. It is difficult to say where the prominent difficulties with enforcement of these laws come from; however, it is apparent that more inquiry and research into this problem is necessary.

High Density Polyethylene Tactile Images

This project was highly focused on the development, implementation, and improvement of a new type of tactile graphic. Current materials used for the presentation of visual materials for blind and VI students include the use of embossed or raised drawings. These drawings, though useful, are often simplified from the original image. This simplification can mislead students or place them at a disadvantage when compared to the original level of image detail their peers are receiving. The new process of creating a high density polyethylene (HDPE) tactile image is simple to implement and has been found to be discernable to those with and without visual impairment.

Research in developing these tactile graphics began in 2012. The 3D tactile image is unique because it preserves the majority of detail found in the visual image.

Furthermore, it includes the different levels of intensity found within the original image that will give it additional contrasting detail. For example, the image will appear taller and more defined in correlation to the brighter regions of the visual image, and shorter and duller in correlation to the dimmer regions.

The tactile images are created using a Computer Numeric Code (CNC) machine and High Density Polyethylene (HDPE) plastic. The CNC machine is able to take a computerized image and mill it into the plastic material. The high quality and durability of the boards makes them ideal for long term use in educational settings. The process for creating the boards will be discussed in great depth in future sections.

Current Research

The research presented here is focused on the search for methods to improve STEM education for blind and VI students as well as the brief inquiry into current problems with its implementation. This research aims to determine whether the use of a newly developed form of tactile graphic could serve as a tool to increase participation and understanding of STEM materials for blind and VI students. A detailed description of the methods used to produce these HDPE tactile boards will also be discussed. Furthermore, the usefulness of adapted materials, accessible technologies, and the use of accessible teaching materials are also evaluated. These evaluations were based on observations, interviews, and scores on various activities.

The information presented in this research summary will include discussion and comparison of previous studies as well as the introduction of new study results. The new material will include results obtained through interviews and evaluations. Many of the

interviews are focused on the experiences of blind and VI students regarding STEM education. The evaluations are primarily focused on the assessment of tactile image usefulness, material types, and accessible teaching materials used to improve understanding upon completion of a science task by blind and VI children and adults.



Fig. 1. President George Bush Signing the ADA into Law. (Image courtesy of Wikipedia Creative Commons.)

Chapter 2. 3D IMAGINE at Arizona State University

Images, figures, and graphics used in STEM education are vital to the complete understanding of the material being taught. Biology students are shown a picture depicting the organelles of a cell, while they are studying them. Astronomy students must learn to identify specific constellations, while viewing a star strewn image of the sky. However, it appears that blind and VI students are not being provided with adequate access to these materials. According to Lederman, et al. (1990), the majority of VI students are provided with simple embossed braille labeled images or even basic text image descriptions. These embossed images are often simplified versions of the image they aim to represent, leaving out crucial information. They are often compared to using a stick figure drawing to illustrate what a person looks like. Furthermore, the images are often based on an interpreter's understanding of the image, which may not always be adequate. For instance, the purpose of a figure may be to demonstrate how chromosomes are split during cell division, but the interpreter creating the embossed image may not know which part of the image contains chromosomes. Verbal and written descriptions also present the problem of bias on the part of the describer. This prevents blind and VI students from interpreting and gaining an understanding of the graphics in the same way their peers are. This inferior method of providing graphic information to blind and VI students appears to be an issue preventing increased participation in STEM fields.

A study of blind and VI students ages 7-12 recently concluded that these students were an average of one and a half years behind their peers in STEM subjects (Wagner, et al, 2003). This divergence appears only to increase over time. Another study found that

students ages 13-16 were an average of 3 years behind their peers in STEM subjects. The majority of these students are provided with text materials in a reasonable format (braille, large print, etc.). Therefore, it is very likely that these results are due to a lack of accessible graphic materials for these students. By ending high school with far less foundation in STEM subjects, blind and VI students face a significant disadvantage when entering college.

The enrollment of blind and VI students in STEM courses at the university level has been historically low. In fact, the majority of universities allow blind and VI students a waiver to avoid these courses altogether, while still being able to complete their degree. Arizona State University does not allow this option. Since completing one science course (with a lab component) is a requirement for every bachelor's degree at ASU, blind and VI students face a challenge. They often fight through these courses with the help of the Disability Resource Center. They are provided with accessible text materials, a note taker, and basic tactile graphics as described previously. All of these accommodations appear to be helpful and beneficial to the students using them. However, very few of these students take on the science courses with enthusiasm and even fewer choose to pursue this area of study further.

In 2012, an interdisciplinary team of staff and students at Arizona State University came together to form 3D IMAGINE. 3D IMAGINE, or "3D Image Arrays to Graphically Implement New Education," sought to create potential solutions in order to increase the participation of blind and VI students in university science courses. A large component of the project was the goal of creating a new type of tactile graphic. The aim

of the new tactile graphics was to provide detailed tactile information to the blind user with a focus on STEM subjects. Other goals of the project were to analyze the need for improved tactile images and determine other methods of maximizing the accessibility of science courses.

In order to meet project goals, the 3D IMAGINE team implemented two fully accessible lab courses. Accessible materials were implemented in introductory astronomy (AST 113) and introductory biology (BIO 100) during the 2012 fall semester. Both lab sections were taught by teaching assistants who were also assigned to teach conventional lab sections for the same course. Most blind and VI individuals will not pursue science degrees, but they are still required to take at least one science course. These courses were chosen because they represented popular choices for non-major science credits.

Making the Graphics

The initial task of the 3D IMAGINE team was to determine an improved method of providing tactile graphics. The team, which included scientists, artists, and engineers, sought to test multiple strategies in order to determine the best material and method of production. This required careful analysis and feedback on a wide variety of physical materials. Other considerations included cost, availability of resources, and analysis of detailed tactile features.

Although increasingly popular, 3D printing was quickly rejected as an option for the purpose of the project. The high cost of 3D printers and materials, coupled with the size and durability disadvantages of 3D printing, made it a poor option. An acrylic

polymer called Corian was tested, but found to be too sharp for tactile interpretation. Another material, medium density fiber board, was originally thought to be a good choice. However, upon further research it was excluded since it contained traces of chemicals including formaldehyde (Figure 2).

After multiple trials and test graphics, the team settled on the use of High Density Polyethylene (HDPE) as the material to use and computer numeric code (CNC) milling as the method of production. The HDPE boards proved to be a cost effective and durable material for the production of tactile images. The material is often compared to the plastic used to make kitchen cutting boards, and is readily available for purchase. CNC is already a common method of producing tactile braille signage for public venues. It provides a low-cost method of producing reasonably sized and durable tactile graphics. By using a CNC machine, the artists could use computer software to design the tactile image, while maintaining crucial points of the actual image. The detailed methodology used to produce these 3D images will be discussed in later sections.

Once the method and material were decided, the team needed to analyze the best dimensions and tactile elements to produce. Since most images were going to be labeled in braille, the boards needed to be a large enough size to include the image and the braille labels. Furthermore, the tactile image itself needed to meet generalized height standards. It would be problematic to have images that were too tall or images that were too flat. The 3D IMAGINE team decided to use the American National Standard: 2003 Accessible and Usable Buildings and Facilities measurements for the production of the HDPE tactile graphics. These standards appear in Table 1.

One of the many benefits of producing the HDPE boards, was the ability to use an intensity based tactile array. This means the computer software could be used to transform images into a grey scale image, then produce a tactile graphic that conveyed this information through a height field. For instance, a bright star on a constellation map would appear very tall on a tactile image, while a dull star would appear short and flat. This benefit also proved useful when trying to convey 3 dimensionality from an original 2D image. For example, a 2D image of a skull could be conveyed tactilely with rounded edges depicting the curvature of the skull. By providing a tactile version of the original image, while using intensity to convey further information, the 3D HDPE boards already far surpass conventional tactile graphics.

Improving the labs

Once the method of production was decided, the team took steps to redesign the lab activities for the astronomy and biology pilot courses. Labs were enhanced with tactile materials, including the HDPE boards, and made accessible. The goal was to provide accessibility to blind and VI students, while evaluating the usefulness of the materials in completing the course work. For example, the astronomy labs included tactile images of constellations that could be used by blind students to help them “see” the stars. There were also tactile tools used in a crater lab that allowed all the students to use touch and hands on approaches to the activity. In the biology lab, conventional lab activities, such as the predator and prey lab were adapted to tactile formats. In the original predator prey lab, colored dots are sprinkled onto a multi colored piece of fabric. Students are then asked to pick up dots at random, the idea being that dots that are able to

hide in the colored fabric are surviving prey. This lab was adapted to enhance the activity for all students. The students were provided with tactile objects such as beads, paper clips, cotton balls, and other items. They were asked to sprinkle these items onto a small square of carpet. When they were then asked to pick up items at random with the lights turned off, many students were excited to find the activity taught them something. Small items were able to hide in the carpet, much the way small animals hide in the tall grass or greenery.

Some of the standard lab activities, including the predator prey lab mentioned above, appeared to be outdated and in need of some improvement. The incorporation of tactile materials provided a method of re-creating these labs while providing accessibility. For instance, a taxonomy lab taught in the BIO 100 course was redesigned with the HDPE series of monkeys based on the images provided in the handout. The images provided were in different scales, illustrated monkeys in a variety of poses, and some made it difficult to clearly see all the animal features due to furry faces. An example image from the original lab can be seen in Figure 3.

Due to the great variety in the images provided, it was difficult to accurately categorize these monkeys into taxonomic groups. In this case, the 3D IMAGINE team was able to obtain 2D images of skulls for each of the monkeys depicted in the original lab. The use of skull images (which were also of an accurate scale) provided a more realistic and consistent comparison of the features of the monkeys. The skull images were also made into 3D images on the HDPE boards. Figure 3 illustrates the transformation from an original 2D image into a 3D tactile HDPE image. By creating

tactile versions of the skull images, students were able to touch and interact with the images. This allowed for more descriptive taxonomic categories such as “size of eye sockets” and “size of teeth.” The features students were able to identify from the HDPE boards would have been more difficult to distinguish in the original images provided.

Pilot Course Results

The quiz and lab report scores from the accessible lab sections were compared to the other lab sections being taught in the conventional way. Comparison of these grades showed that scores in the accessible sections were higher than those of regular sections. An interesting finding revealed that the sighted students in the accessible courses were also benefiting from the use of the tactile materials. In each lab section that offered tactile enhancements, sighted students were also invited to use the materials. Many of these students stated that use of the tactile images (and other materials) made the labs more interesting and fun. These statements, coupled with high scores, suggest that the tactile materials could possibly enhance lab courses for all students. The results of sighted and blind student’s surveys from the accessible section of BIO 100 can be seen in Table 2.

Participation Study

Although the results gleaned from the pilot astronomy and biology courses demonstrated the potential benefits of the tactile materials, the participation of blind and VI students in the courses was still low. This makes the data difficult to use in demonstrating solid evidence of the need for the tactile boards. With this problem in mind, the 3D IMAGINE team decided to arrange a participation study in order to gather more data. The study consisted of two lab activities over the course of two days. Each

activity was presented and taught in the same way as a normal lab session in an ASU course. The activities in the study were led by trained teaching assistants.

Blind and VI adults in the community were invited to participate in the study and received a gift card as compensation for their participation. Participants were given HDPE boards or standard embossed images at random, with half the group receiving HDPE and half the group receiving standard embossed images. Each participant was also given lab directions in the medium of their choosing (i.e. braille, large print, read aloud). The participants were allowed to work in groups, in the same way a standard lab course would allow, and asked to complete the lab activity. Each activity, one astronomy and one biology, included a set of questions testing the understanding of the materials.

Although allowed to discuss and work in groups, participants were required to answer the activity questions individually. The results of the questions were later compared between participants using the HDPE boards and those using standard embossed images. The results of the scores from the participation study were promising. The data showed that participants using the HDPE materials scored as much as 60% higher than those not using the boards. Furthermore, all participants were also surveyed and all had positive feedback on the enhanced tactile materials. These results demonstrate the benefits of including the improved HDPE tactile graphics in science courses.

Summary

Inclusion of adequate accessible tactile materials in STEM courses, particularly on the university level, continues to be an issue. This is likely a large contributing factor

in the steadily low participation of blind and VI individuals in these courses. The 3D IMAGINE team at ASU has demonstrated a potential solution to this issue. The careful creation of enhanced 3D tactile graphics on HDPE boards, has illustrated the impressive potential to improve accessibility to the blind. This potential was demonstrated by the inclusion of the HDPE boards and other tactile materials in two pilot courses at ASU. In these courses, both sighted and blind students showed increased scores in addition to increased enthusiasm for course material.

A further study of the benefits of the HDPE boards was conducted with blind and VI adults in the community. This study verified and increased the data supporting the usefulness of the tactile HDPE boards in the completion of science activities. By including more detailed and accurate tactile images, created using HDPE and CNC milling, blind students may have better experiences in the sciences.

Table 1: American National Standards for Braille Signage (2003)

The following table outlines the braille standards followed by the 3D IMAGINE team in the production of HDPE tactile graphics (Hasper, et al., 2014).

	Minimum in Inches Maximum in Inches
Dot Base Diameter	0.059 (1.5mm) to 0.063 (1.6mm)
Distance between two dots in the same cell	0.090 (2.3mm) to 0.100 (2.5mm)
Distance between corresponding dots in adjacent cells	0.241 (6.1mm) to 0.300 (7.6mm)
Dot height	0.025 (0.6mm) to 0.037 (0.9mm)
Distance between corresponding dots from one cell directly below	0.395 (10.0mm) to 0.400 (10.2mm)

Table 2: Survey Results in a BIO 100 Lab Section

All students in the accessible section of BIO 100 were asked to rate the following statements on a scale of 1-5 (n = 25).

Statement:	Score:
3D materials helped understanding of concepts.	3.75
Made assignment more interesting.	4.43
Helped answer questions.	3.64

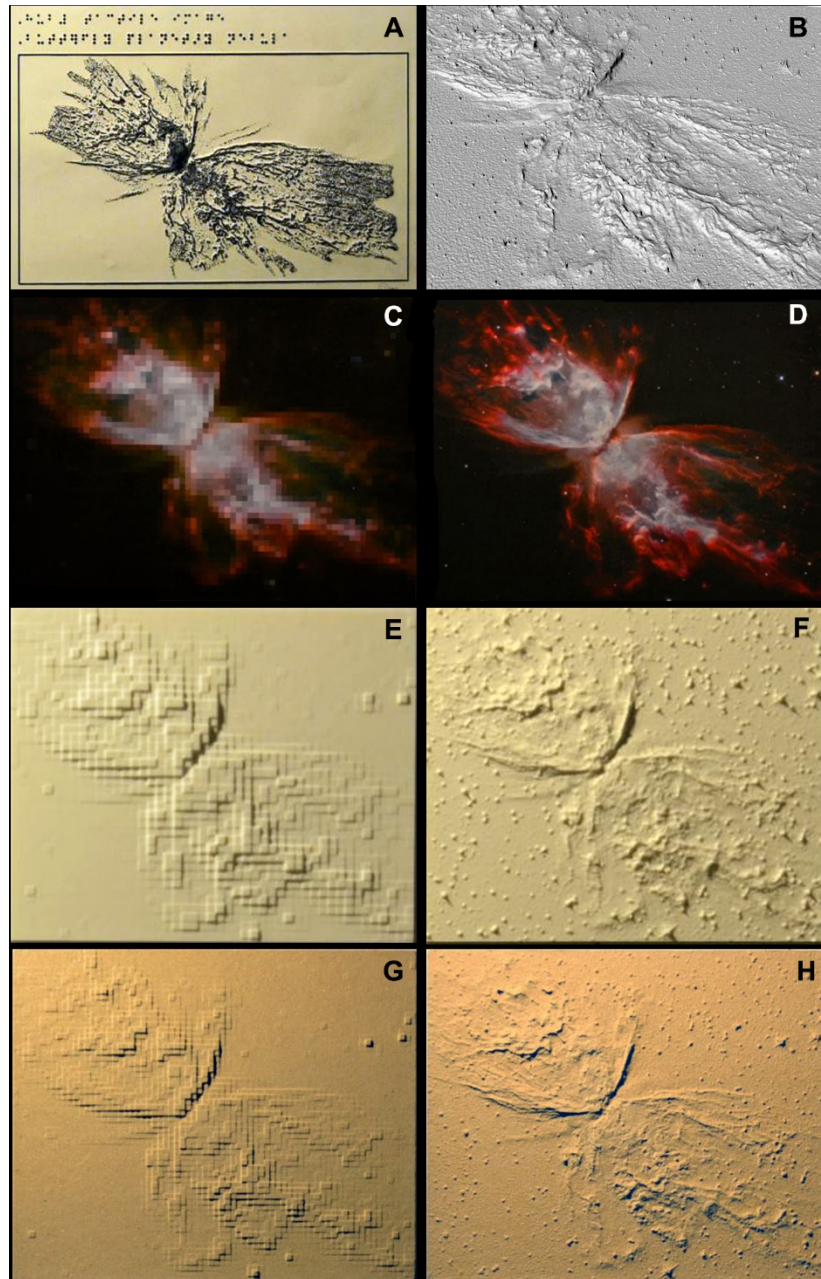


Fig. 2. Comparison of different substrates and resolution to create tactile images. The Hubble Space Telescope Butterfly Nebula image was tested in various formats including raised print (A), HDP (B), low resolution (C) and high resolution (D) print as well as using Corian (E, F) and the medium density fiberboard (G, H) in low and high resolution (E,G: F,H). The higher resolution images were better able to highlight smaller stars found within the image. (Butterfly Nebula Image source: Mechtley et al., 2012).



Fig. 3. Chimpanzee 2D Images Compared with a 3D Tactile Image Format. An original chimpanzee 2D image (A) is compared to the 2D print (B) and 3D tactile (C) chimpanzee skull image used in a revised BIO100 taxonomy lab. (Image A courtesy of Wikipedia Creative Commons.)

Chapter 3. Testing New Methods and Materials

There were significant results following the pilot courses and participation study. Two conclusions in particular necessitated further exploration. There was still a clear issue of low participation. Although a few blind students did sign up for the courses at the university level, it was very difficult to persuade others. Furthermore, the completion of one science course is not likely to convince students to change majors or be willing to pursue a science degree. This information led to the idea of working towards building a pipeline of VI youth starting at a K-12 level.

Another finding gathered from the pilot study, was the benefit of tactile materials for sighted students. The concept of using tactile modes of instruction is not a new one. In fact, several studies indicate the high potential benefits of incorporation of tactile materials. A study of an introductory biochemistry course conducted at DePauw University strongly supported this theory. The study results indicated that student's scores on a pretest and subsequent posttest improved from 8% of fully correct answers to 67% of fully correct answers, following the inclusion of tactile models (Roberts, et al., 2005). Furthermore, results from a student survey showed that tactile models received the highest ranking for valued learning tool out of seven other course materials. Such studies, coupled with the findings from the pilot courses, prompted further research to determine the feasibility of using HDPE boards as a tactile supplement to current course materials. However, since the HDPE boards were originally made for blind students, it was important to first determine the possibility of creating a K-12 pipeline of students.

Perhaps working with younger blind and VI students, who have not yet convinced themselves that science is out of reach, could create a larger impact in the years to come.

The Foundation for Blind Children

There are several nonprofit organizations dedicated to providing services to the blind and VI community. Phoenix Arizona has an organization called “The Foundation for Blind Children,” or FBC. FBC provides preschool and kindergarten classes to students that are blind, visually impaired, or have multiple disabilities. The long term goal for many of these students is to transition them to public schools. FBC works with parents and schools to supplement the services provided by school districts in order to make these transitions smooth. In addition to these services, FBC also has several programs that assist the blind and VI population. These programs include a college preparation program, a work preparation program, and an adult services program. These programs assist blind individuals at various stages of life to successfully achieve their goals.

One of FBC’s most utilized programs is “Sports, Habilitation, Arts and Recreation Program,” or “SHARP.” This program provides fun and accessible activities to K-12 students every Saturday. In addition, SHARP also provides camping and field trip opportunities. Students get a chance to participate in beep ball games (beeping baseball), create tactile art, and even cook elaborate meals with accessible tools. This program was a great platform to begin the incorporation of accessible science for the K-12 age group.

Members of the 3D IMAGINE team and other volunteers began conducting monthly activities at the FBC SHARP program in fall 2013. The workshops would consist of a science lesson, taught by the volunteers and incorporating accessibility. The activities usually consisted of tactile images, accessible reading materials, and a hands-on project to reiterate the lesson. Each activity was also delivered in an age appropriate task, with the students often being divided into elementary, middle, and high school groups. All of these activities were completely accessible and helped the students build on science concepts they were being taught in school.

An example of one of these activities was a neuron lab. Students were given tactile images of neurons, made on HDPE boards (Figure 4). They were also given supplemental reading materials that explained what a neuron was and the basics of how neurons work. A lesson was then taught in which students were asked to touch and explore the tactile graphics while listening. They learned about axons and dendrites, while getting an opportunity to touch a tactile picture of them. Students were then given pipe cleaners of differing textures, colors (for those with low vision) and sizes. They were asked to build their own neurons using the pipe cleaners. Many students were able to successfully construct a complete neuron, including a cell body, axons, and dendrites. This activity demonstrated that the students understood the material being taught in the lesson. It is likely that supplementing the lesson with tactile images of neurons helped to bolster student understanding.

Other science activities for SHARP students demonstrated similar success. For instance, the students got an opportunity to learn about forensic science and the use of

fingerprints at crime scenes. In this activity, students had the opportunity to learn about very detailed fingerprint patterns and to touch them on tactile HDPE boards. In addition, students own fingerprints were taken, enlarged, and made into tactile images for each student (Figure 5). This was done with the use of special swell paper which contains microbeads that expand when heated. Heat will be concentrated on areas where ink is printed and generates a tactile image. This activity greatly impressed the FBC CEO, Mark Ashton. “Ashleigh used a student's own fingerprints to make science fun, important and personal. More importantly, Ashleigh proves to our kids that STEM careers are attainable without sight.” Having learned about the different fingerprint patterns through tactile graphics, students were able to identify the patterns on their own fingerprints. This use of tactile information greatly increased the student’s understanding of the material and made the lesson more engaging.

Special sessions were created in a tactile format to teach lessons in chemistry, forensic science, and cell biology. All activities were found to be very enjoyable and beneficial to the students. The SHARP program director, Cody Franklin, said: “From my observations the students have been incredibly engaged in the activities and learned a lot. They enjoy the activities and really seem to have a better understanding of the concepts that are being taught due to the hands on activities.” Franklin also commented that students seemed excited when they were informed they would be doing science activities. She expressed how important these activities were to the students. Explaining that STEM careers are going to continue to be important in the future and that giving these students a chance to participate in STEM was vital. “Without giving these kids a

chance to experience STEM, the world is missing out on a whole population of potentially great scientists and mathematicians,” Franklin stated.

The students also greatly appreciated the chance to participate in these activities. There were about 25-50 students per workshop and three of these students showed particular interest every time the research team conducted a workshop. These students will be identified as Student A, Student B, and Student C. The students were interviewed and observed throughout the research process to gauge their excitement and interest. Student A attended the SHARP program regularly and was eager to answer questions directed at the students during the lessons. He stated that science was his favorite subject in school, but that he often felt “left out.” Student B expressed her increased interest participating in science classes in college and perhaps pursuing a science career. “I really liked the fingerprints; I think I want to be a forensic scientist.” She explained that getting a chance to do science with accessible tools showed her that it might be possible for her to become a scientist. Student C did not wish to be interviewed, but often showed great enthusiasm for learning science concepts. She was quick to answer questions about the material that was taught in each lesson. As a group, the students sometimes appeared disinterested in doing what was perceived as school work. However, as the activities progressed, becoming increasingly hands on, the student’s engagement and interest greatly improved.

Conclusions and Future Plans with FBC

Although no numerical data was collected, the observations gleaned from the workshops done with the Foundation for Blind Children’s SHARP program were helpful

to this research. The students appeared engaged and excited about the STEM activities when they were presented in an accessible format. The students that were interviewed showed increased enthusiasm over time and the possible interest in pursuing science further. According to the SHARP program director, the students she observed were engaged and excited about the activities and even inquired about future science activities. All of this observational information demonstrates the benefits of increasing accessible materials for K-12 science lessons. This study demonstrated the need to research these observations in a k-12 classroom setting, where standardized academic measurements and comparisons can be made.

Future plans with the FBC SHARP program include the possibility of creating a fully accessible science camp. This camp would be available to SHARP students interested in pursuing further science education and careers. It will include several science lessons and workshops (similar to those conducted previously at the FBC). In addition, students will be given the opportunity to create and present their own scientific research. This program will include accessible materials for all participants, allowing them the freedom to explore and learn with no concern about accessibility. Ideally, each student will also have a college mentor studying a STEM subject. This mentor would be there to guide the student's project, give advice about college, and assist students with questions about pursuing science education and careers. As a whole, the goal of the camp will be to provide interested blind and VI students a glimpse of their possible future in STEM. It will demonstrate (on a smaller scale) the structure of conducting research and studying science. Most importantly, it will demonstrate that implementing accessible materials will have a great impact on blind students' potential to excel in STEM.

Other Studies Conducted With Tactile Graphics

The implementation of the 3D HDPE boards in the two pilot courses at ASU demonstrated the usefulness of these materials for all students. Since the boards have the potential to benefit sighted students in addition to blind students, further research with sighted individuals was conducted. A study was conducted with participants visiting the Phoenix Zoo for a family event. Participants were asked to close their eyes and use their hands to interpret a tactile image. The tactile HDPE board was placed into a box, covering the image from view (Figure 6). The participants were then asked to explain what the image was, using only touch. The first task involved identifying a simple shape such as a triangle, circle, or square. The second task involved identifying a more complex image such as a fish, a brain, or sea shell. The results of the study can be viewed in Table 3A and 3B.

Some general trends appeared from the results of the study at the Phoenix Zoo. It seems that the ability to tactilely discern an image increased with age. Participants in younger groups had a lower average of correct answers, while older participants had a higher average of correct answers. It also appears that a learning curve exists when trying to interpret tactile images. The first task, identifying shapes, had a lower average of correct answers than the second task, identifying images. In fact, the second task had no incorrect answers from all participants. The later trend suggests that the ability to interpret images by touch will simply take some practice. However, the result that all participants correctly identified the tactile image they were asked to interpret in the second task, demonstrates that sighted individuals do have the ability to tactilely discern

complex graphics. With this in mind, there is also reason to believe that introducing tactile images into a standardized classroom, as a supplement to visual materials, may benefit all students.

Although the most common formats for educating are visual and auditory, there may be many students that could benefit from tactile based learning. Common methods of teaching include lecturing, playing a video, or asking students to read text materials. All of which are informative and important. However, some students may need a more active method of learning difficult material. Allowing students a hands-on approach to STEM subjects gives them a physical link to the material they are learning. These methods have already been applied and used in the form of lab exercises. Science courses often include lab activities that help reinforce complex topics being taught in other formats (text, lecture, etc.). These lab components allow students to physically engage with the material and further strengthen their understanding of the topic. In a sense, these activities are tactile versions of the course material. There is strong evidence that providing students with these physical and tactile connections to the material they are learning, can lead to an increase in comprehension. A study of a chemistry class tested this theory. The study found that students that were taught using a hands-on approach and tactile enhancements (molecular models in this case) received an average score of 95% and students taught the same concepts in the traditional methods (text/lecture) received an average score of 80% (Pashler, et al., 2008). Studies such as this one demonstrate the potential benefits of introducing more tactile learning into the average classroom.

The 3D HDPE boards created by the 3D IMAGINE team at ASU may be a simple means of introducing more tactile materials. The boards can be customized for any lesson, topic, or activity. This customization will allow educators to introduce tactile learning where and when they feel it will benefit their students. Since the boards are fairly inexpensive and durable, they will survive years in a classroom. These boards have already demonstrated success for sighted and blind students in the two pilot courses discussed previously. The subsequent Phoenix Zoo study also supports the feasibility of using the boards for sighted individuals. These results, coupled with studies like that of Prashler et al., demonstrate the need to further explore the possibility of using HDPE boards, and other tactile materials, in more classrooms.

Conclusions

The workshops at FBC and the studies at Phoenix Zoo added more supporting information to the work done by the project team. It appears that implementing more accessible materials in STEM classes of young blind and VI children (K-12), could increase comprehension and interest in STEM areas. The students that participated in the STEM workshops at the SHARP program seemed to gain knowledge and excitement for science when they had access to tactile materials. The idea to implement more tactile materials in a general classroom setting was supported by the studies conducted at the Phoenix Zoo. These studies indicate that sighted individuals are also capable of using and interpreting tactile images. Since studies suggest that the use of hands-on materials in a classroom enhances comprehension, it is likely that use of tactile materials will benefit all students. Further research to verify these theories needs to be continued. This

research should involve implementing the 3D HDPE boards and other tactile materials into standard K-12 classrooms in order to determine their benefits for sighted and blind students.

Table 3: Phoenix Zoo Study Results

A. Participants were asked to identify a shape through touch. Simple shapes were presented on 3D tactile HDPE boards. There was a total of 33 participants.

Number of Participants	Male/Female	Age	Percentage Correct
4	Female	4-5	50%
5	Male	4-5	60%
11	Female	6-12	81.8%
7	Male	6-12	57.1%
5	Female	20+	100%
1	Male	20+	100%

B. Participants were asked to identify a tactile image only by touch. Tactile images were presented on 3D HDPE boards. There was a total of 33 participants.

Number of Participants	Male/Female	Age	Percentage Correct
4	Female	4-5	100%
5	Male	4-5	100%
11	Female	6-12	100%
7	Male	6-12	100%
5	Female	20+	100%
1	Male	20+	100%

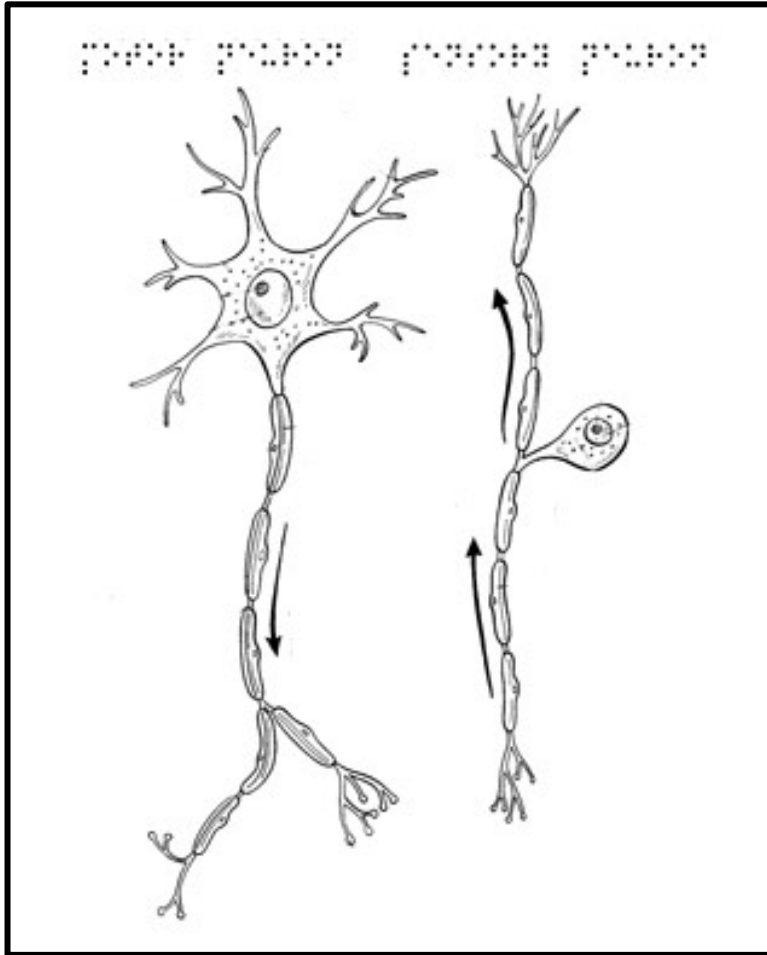


Fig. 4. 3D HDPE Neuron Board. Braille labeled images of neurons were produced as 3D tactile graphics on HDPE boards. These images were used to teach a neuron workshop at Foundation for Blind Children's SHARP Program.



Whorl Fingerprint Pattern

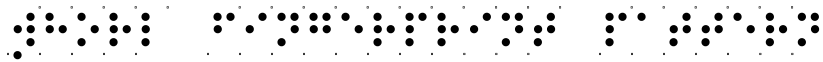


Fig. 5. Tactile Fingerprints. Student's fingerprints were enlarged and printed on special swell paper. This paper is heated in order to create a simple tactile image. Students were each given tactile prints of their own fingerprints.

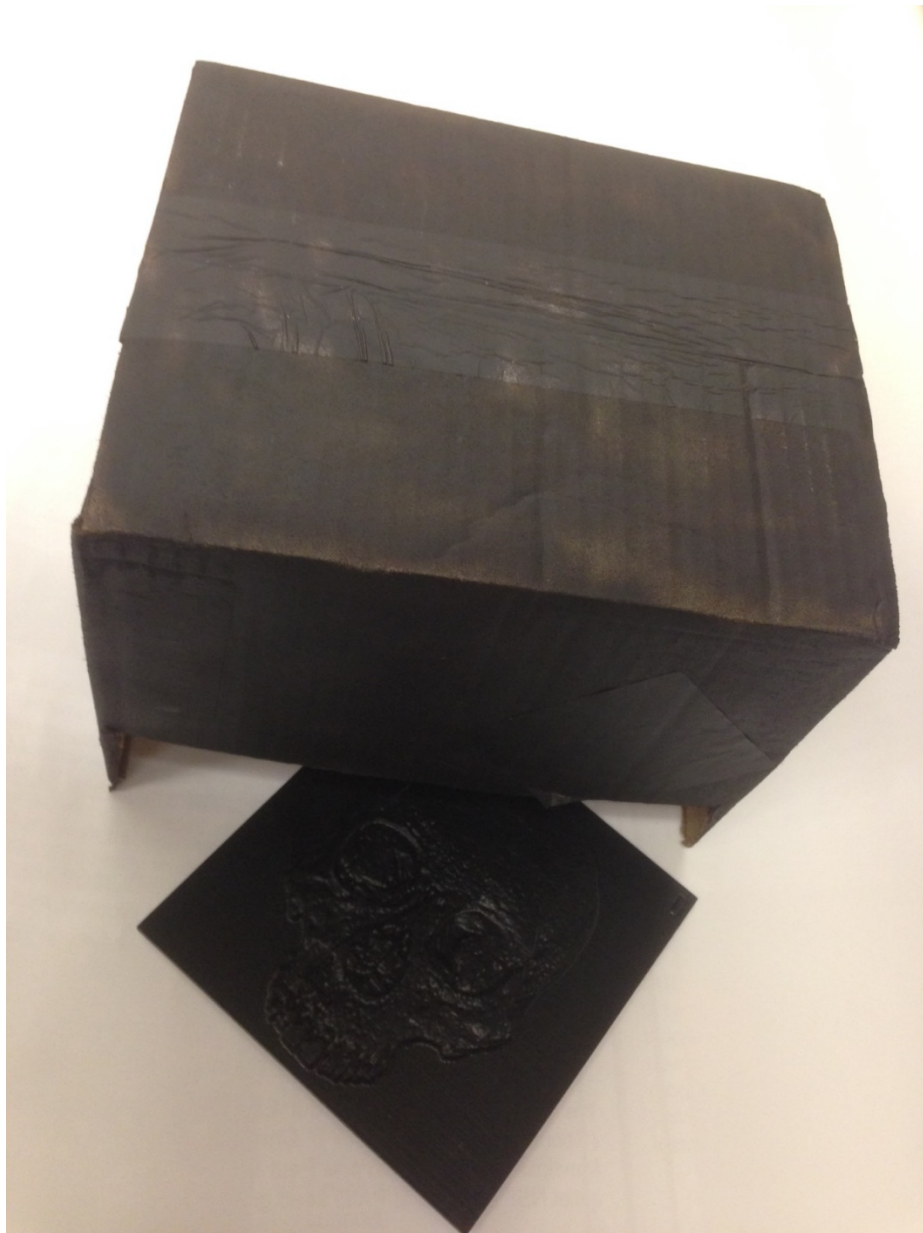


Fig. 6. Covered Box Used to Test Tactile Images on Sighted Individuals. Tactile images were placed into this covered box, preventing any visual interpretation of the images. Participants were then asked to use their hands to discern the tactile image.

Chapter 4. Methods Used to Produce High Density Polyethylene 3D Tactile Images

The 3D tactile graphics used in this research were produced using a computer numeric control machine (CNC). There are several types of CNC machines including CNC lathes and CNC milling machines (“CNC Machine,” 2014). A CNC machine is able to take image data that has been converted into a computer code and precisely mill a 3D relief into hard yet pliable material such as wood, metal or plastics. This technique has been frequently used to produce small components and parts for industry prototypes. CNC is also a technology commonly used to create braille signs for public venues, making it ideal for the production of tactile images.

A CNC milling machine was used with high density polyethylene (HDPE) plastic to produce tactile graphics for this research study. The CNC milling machine is a viable option because of its capability to produce a tactile image that has three dimensions. CNC milling machines are commonly found in college campus workshops, making them a convenient equipment resource for the production of these educational materials. Additionally, the software needed to desaturate and invert images is available through popular programs such as Photoshop that are frequently provided through institutional licenses at many universities.

How a CNC Machine Works

The proper use of a CNC machine requires specialized software and experienced users. The CNC operator must be familiar with the particular interface for the CNC machine being used or be familiar with G-code, the language computers use to “talk” to the milling instrument (Larry, 2012). The operator will have to set up the material being

tooled, including proper alignment and mounting. Next, the operator will need to select the correct size tool bit for the correct stage of milling based on the desired precision of the cut. Finally, the operator must use the CNC program interface or a computer with accompanying software to program the desired job. Once the CNC machine has been programmed with instructions, a drill bit tool will move across the surface of the material being milled. The drill bit will remove material in layers as it rasters across the surface. Typically a large tool bit is initially used to produce a rough rendering of the image and remove the bulk of excess material then it is replaced by finer tool bits to establish a smoother and detailed image.

Although the knowledge needed to properly operate a CNC machine appears complex, training is easily obtained within a few hours. Many universities offer courses on machining which will include proper use of CNC. Most CNC machine manufacturers will also offer onsite training to machine purchasers (Larry, 2012). There are also new centers opening up around the country called tech centers which provide instruments and training to hobbyists and entrepreneurs. With proper training and some experience, it is possible to become a skilled CNC operator.

Production of 3D Graphics for this Research

Experienced CNC machine operators who had advanced training produced all of the 3D tactile images used in this research project. The operators were art and design students at Arizona State University with previous experience and training in the use of CNC machinery and many of whom owned their own machines. Materials were purchased with research funds provided by the College of Liberal Arts and Sciences, the

School of Life Sciences, School of Earth and Space Exploration, NASA, TactilEyes and local foundation funding. Recently the Chandler Tech Shop opened and provides free membership to ASU students. The Tech Shop is where the tactiles are currently being produced. Those interested in using instrumentation at the tech shop can obtain training for a nominal fee which includes safety instruction. More information about The Tech Shop can be found at: http://techshop.ws/ts_chandler.html.

The images used to produce the 3D tactile graphics were either obtained from free creative commons online resources or created by art students. These graphics were used to produce the educational materials used in the pilot courses and participation studies mentioned in prior sections. All images were edited by a member of the research team or by a CNC operator for proper rendering onto the HDPE boards.

Methods and Explanations

Digital pictures are needed in order to create 3D tactile images. The images must be desaturated into a gray scale image. This means any colors on the original image had to be converted into a corresponding shade of gray (Figure 7). The image information must be simplified into gray scale to enhance the tactile features during CNC milling. This will make the brighter (white) regions of the image appear taller (distinctive) on the boards. Occasionally it is necessary to invert the black and white color distribution for proper image production. For example, if a diagram image is used where the outline is black the resulting milled image would be depressed into the board instead of projected outwards. The fingerprint is a good example because it is a line drawing that has line patterns that must be inverted in order for the lines to be make tactically discernable.

The inversion process makes all lines white and the background black (Figure 8). Alternatively, images such as skulls were not inverted because the white skulls were the desired prominent feature of the final tactile image. Because this process is customizable braille labeling was also applied to many of the images.

Once images were converted into the desired gray scale image and labeled, they were saved as JPEG digital image files. The JPEG files were then imported into a computer aided design software (CAD), such as Rhino. Within the CAD software, operators can edit settings that instruct the CNC on the desired outcome of the tactile image. Users can edit clarity and finish settings, in addition to selecting a “height field” option to produce the intensity-based image used in this study. The files were then exported as an STL file type used by 3D programs.

The final process requires that the STL files are imported into a CNC cutting program called Cut 3D where the operator will determine the final cut settings. It is at this point that the operator must also select the proper tool bit size. As described earlier, the bit size will determine the coarseness of the tactile image cut. Another feature available on the milling instrument is the ability to determine the range of clarity by defining the spacing of the raster lines. This will affect the amount of time needed for cutting. Rough initial cuts are used initially to remove excess material and can be performed quickly but for a more smooth and detailed surface additional time will be required with the use of a finer tool. Unfortunately, speeding up the cutting process will result in a lower quality tactile image board with less clarity, and generally rougher to the touch. In order to produce the highest quality tactile graphics, they had to be cut in three

stages. The first being a rough cut with a large tool bit and the subsequent two runs being clearer cuts with finer tools. An image board can take anywhere from two to five hours to produce, depending on the details of the original printed image and size.

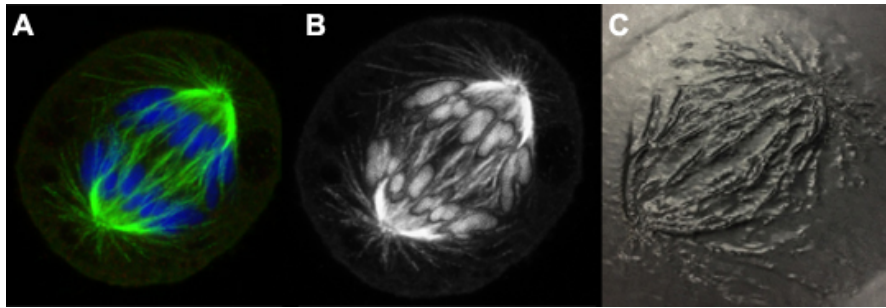


Fig. 7. Gray Scale Conversion of a Color Spectrum. Digital images (A) are converted into gray scale (B) by desaturation so that areas with the highest intensity of color will become the lightest shade of gray. This is represented in the milled HDPE tactile image such that the brightest areas will project out higher than the dim regions (C).

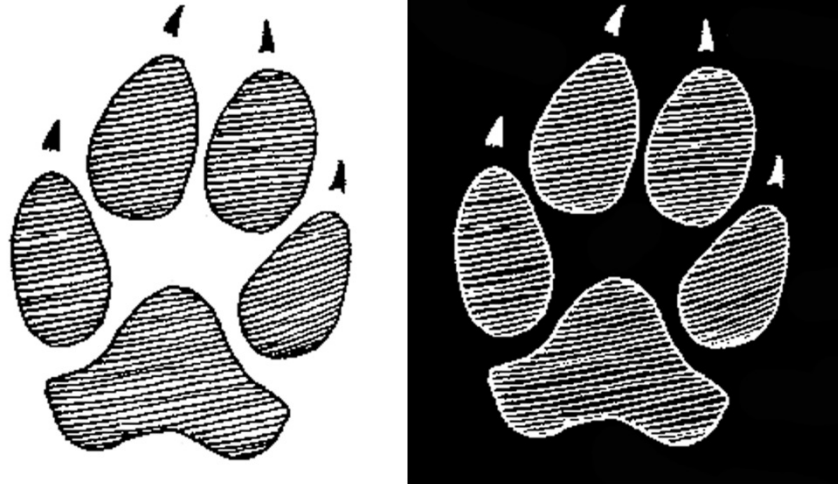


Fig. 8. Image of a Canine Paw Print before and after Inversion. The image of a canine paw print, originally printed as black on white, is inverted so that the new image will represent the most intense regions as white and the dim regions black. This conversion will result in the most prominent features being projected highest in the final tactile image board.

Chapter 5. Project Outcomes and Conclusions

Despite the implementation of laws such as the American's with Disabilities Act (ADA) and the Individuals with Disabilities Education Act (IDEA), there are still issues regarding education for students with disabilities. These difficulties are partially due to a lack of adequate accommodations. Blind and visually impaired individuals are consistently behind their peers in STEM subjects such as math and science. This deficit can likely be attributed to the lack of accessible images provided to blind and VI students.

Science, Technology, Engineering, and Mathematics (STEM) tend to be heavily reliant on image based information. Without adequately descriptive and informative tactile images, blind and VI students are not being provided with the materials they need to succeed. The creation and subsequent improvement of 3D images made on HDPE boards could serve as a solution to this issue. The HDPE boards are unique in comparison to current tactile materials because they provide advanced levels of detail. These details include the ability to use intensity based information in a tactile format.

The research conducted for this project sought to determine if the use of HDPE boards had the potential to increase the participation and success of blind and VI individuals in STEM fields. The two pilot courses at ASU demonstrated that the boards were beneficial to blind students as well as potentially beneficial to sighted students in an academic setting. Data collected through the participation study with blind adults from the community, demonstrated that the use of the HDPE images significantly improved the performance of these individuals upon completion of various science activities. The research study conducted at the Phoenix Zoo provided evidence that tactile manipulatives

can also help sighted individuals as a supplement to visual images. Furthermore, the student observations at the Foundation for Blind Children demonstrated an increased interest and excitement for STEM, when blind students are consistently provided with accessible tactile materials.

The conclusions drawn from this project support the theory that the inclusion of tactile HDPE images has high potential for the improvement of STEM education for blind and visually impaired students. Future research should seek to determine to what degree these new 3D images are useful for blind and visually impaired students taking STEM subjects. The research should also evaluate the degree of usefulness the 3D images has for sighted students in an academic setting. Because few college age students who are blind or visually impaired will seek a STEM degree because of negative experiences, additional studies should be conducted at the K-12 level to regain the interest of these students and hopefully increase the number of students who will seek a college education or career in STEM.

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APPENDIX A
IRB DISCLOSURE STATEMENT

The research conducted in this study was approved under the Arizona State University Internal Review Board (IRB) protocol # 1207007997 for the project titled STEM Course Enhancement for the Visually Impaired [3D IMAGINE].

APPENDIX B
SURVEY QUESTIONNAIRE

During these lab exercises we introduced 3D tactile materials that supplemented the existing vision enriched materials which are typically provided in the lab. These efforts are part of a study that is investigating ways to improve the accessibility of STEM (science, technology, engineering and mathematics) courses for the visually impaired. We are requesting your feedback in regards to how these new materials assisted you in completing the assigned tasks.

1. Please select from the following list which statement best describes your level of vision:

- normal vision
- low vision
- legally blind
- totally blind

2. When did you lose your vision?

- N/A
- 0-3yrs old
- 3-6yrs old
- 6-12yrs old
- 12-14yrs old
- 14-18yrs old
- during adulthood

3. From the list below select your current level of education:

- high school education
- some college
- college degree (including either associates or bachelors)
- some graduate education
- graduate or medical degree

4. Check which classes have you taken at the college level?

- Science
- Math
- Technology (i.e. computer science)
- Engineering

5. Please rate your experience on a scale of 1-5 (5 being the best) on how well the 3D materials helped you.

- 1 2 3 4 5 The 3D materials helped me better understand the lab's concepts.
- 1 2 3 4 5 The 3D materials made the assignment more interesting.
- 1 2 3 4 5 The 3D materials helped me answer the assigned questions.

6. After using the tactile boards and from your experience and understanding of printed pictures, do you feel the boards represent an accurate representation of a 2D image?
7. After using the 3D tactiles do you have any recommendations on how these could be improved for these or similar lab exercises?
8. Are there any other suggestions or comments that you would like to provide in regards to making STEM based labs more accessible to the visually impaired?
9. In general, if STEM information were converted into a tactile 3D format, similar to what you used today, would this increase your interest to learn more about these disciplines?
10. If this 3D formatted material were available when you were younger (for example elementary, middle or high school level) do you think you would have had an increase your interest to learn more about science, technology, engineering or mathematics?
11. What is your gender [OPTIONAL]? _____ Male or _____ Female
12. What is your race/ethnicity [OPTIONAL]:
- _____ White (non-Hispanic) _____ African American _____ Native American,
_____ Hispanic/Latino, _____ Asian/Pacific Islander _____ Other (please specify).

BIOGRAPHICAL SKETCH

Ashleigh Gonzales graduated from Arizona State University with a bachelor's degree in Molecular Biosciences and Biotechnology. She chose to complete her master's research in the area of STEM education for students who are blind and visually impaired. Having experienced many difficulties in the completion of her degree and realizing the issues with regards to accessible materials for blind students, she was compelled to research possible solutions for herself and others. With a collaborative team of researchers at ASU, Ashleigh began her graduate studies through a project called 3D IMAGINE. The 3D IMAGINE team successfully developed a new form of tactile image for the blind and visually impaired. She also successfully started a non-profit organization, Tactileyes, with research partners. Tactileyes makes and distributes tactile HDPE images free of charge for use in educational settings. She has also conducted research on the development of accessible lab tools for cell culturing protocols. Ashleigh hopes to use her experiences and education to help blind and visually impaired students pursue science.