Methods for Creating and Evaluating 3D Tactile Images to Teach STEM Courses to the Visually Impaired

By Eric Hasper, Rogier A. Windhorst, Terri Hedgpeth, Leanne Van Tuyl, Ashleigh Gonzales, Brittany Martinez, Hongyu Yu, Zoltan Farkas, and Debra P. Baluch.

Project 3D IMAGINE or 3D Image Arrays to Graphically Implement New Education is a pilot study that researches the effectiveness of incorporating 3D tactile images, which are critical for learning science, technology, engineering, and mathematics, into entry-level lab courses. The focus of this project is to increase the participation and performance of blind or visually impaired (BVI) students by providing a multimodal tactile approach to learning image-rich material. This study explored the use of various tactile image formats and activity sets to evaluate their ability to assist students in lab exercise. These haptic tools were evaluated in classes that had both sighted and BVI students as well as in participation studies comprised primarily of individuals with vision impairment. The results of this study demonstrated that the inclusion of tactile images is helpful to both sighted and vision-impaired students and should be explored further to determine the extent of their educational benefit.

Images are an important component of science, technology, engineering, and mathematics (STEM) education and are often inaccessible to those who are blind or visually impaired (BVI). The tools that are made available to these students in public school for learning and understanding STEM primarily consist of braille text with embossed images or image descriptions (Lederman, Klatzky, Chataway, & Summers, 1990). Although image substitutes are provided to assist students with understanding STEM course material, they are often overly simplified and miss most of the relevant information that is crucial to learning the particular concepts being taught. Quite often, images are omitted from the resource materials and are replaced by verbal descriptions that have been annotated by non-STEM based employees. Although image descriptions may be useful, it is still considered a secondary level of interpretation, and many important details have been reported by BVI students to be left out or misinterpreted. This is an inferior method of conveying visual information because BVI students are required to rely on someone else's interpretation of an image, which for sighted students is part of the natural learning process.

According to the American Foundation of the Blind (AFB; 1999), there are over 7 million visually impaired people in the United States (Kirchner, Schmeidler, & Todorov, 1999). In 2004, of the 11,074 BVI clients served by state and federal vocational rehabilitation programs, less than 5% (or 522) were employed in STEM fields. Of these 522, only 16 entered occupations in mathematics and physical sciences (Blackorby, Chorost, Garza, & Guzman, 2003; Cavenaugh, Giesen, & Steinman, 2006). In an effort to address these concerns, research funding continues to be provided by funding agencies such as the National Science Foundation to find solutions, because despite many notable efforts to date, students with disabilities continue to be underrepresented in STEM educational and career development opportunities.

With such a bleak representation of BVI individuals continuing into the workforce, there have been many studies conducted to identify when the disparity of STEM education may begin to occur, as well as potential causes. A Special Education Elementary Longitudinal Study found that BVI students (ages 7 to 12 when entering the study) were approximately 1.5 years behind grade level in mathematics (Wagner et al., 2003). In a similar study, the National Longitudinal Transition Study-2 found that BVI students (ages 13 to 16) were an additional 3 years behind their peers at the same grade level (Wagner, Newman, Cameto, & Levine, 2006). Further reports have found that in the 1980s, 70% of working-age BVI individuals were underemployed or unemployed (Ryles, 1996; Schroeder, 1989), and from the 30% who were employed, 85% read braille (Ponchillia, Lee, & Moore, 2008; Spungin, 1996). By 2000, these statistics had shifted, with only 26% of BVI individuals employed, and of those 85% read braille (Maurer, 2000; Spungin & D'Andrea, 2000).

These statistics suggest that the ability to read braille is not enough to motivate and engage a BVI learner. Within STEM disciplines, images convey not only critical information, but also draw the interest and enthusiasm of the student. If one were to explain the vast expansion of the universe without using pictures, it would require many descriptive phrases to fully relay an understanding of this concept. But if this description were also accompanied by an illustration that helped in visualizing the spatial relationships of space and its contents, additional descriptions would not be required. Pictures and manipulatives are frequently used in primary education because they add an additional modality to the foundational learning process. Images are a required component needed by all students, including those who are blind or visually impaired, to facilitate the learning process and peak interest in learning core concepts.

Current enrollment data at Arizona State University (ASU) show that BVI students have a history of low enrollment in lab-based STEM courses. Historically, many universities have opted to allow these students to receive a waiver from the lab requirement of these courses, in an effort to increase enrollment and avoid the challenges of making these labs accessible. At ASU this is not an option, and BVI students must work with the Disability Resource Center and instructor to provide accommodations on an as-needed basis. Although this approach removes some of the obstacles that prohibit a visually impaired student from taking a STEM lab, these additional efforts do not encourage students to pursue this degree or career path. This study has found that when 3D tactile images and activities were incorporated into the lab design, interest increased for both sighted and visually impaired students.

The Project 3D-IMAGINE (3D Image Arrays to Graphically Implement New Education) team is comprised of interdisciplinary researchers who incorporate 3D tactile images into STEM lab classes to test their ability to improve the participation and performance of visually impaired and blind students. The project goal is to identify and overcome potential obstacles encountered by BVI students, specifically by converting visual-based materials and activities into a tactile format. Beginning in the fall 2012 semester, project team members began to evaluate pilot labs in astronomy and biology to determine how these could be enhanced with tactile materials that would increase the educational effectiveness as well as accessibility for all students. Introductory nonmajor courses were chosen for the pilot because of the historic low enrollment of students with visual impairment in STEM de-

FIGURE 1

Student testing the resolution and clarity of an image created from high-density plastic.

gree programs. Nonmajor astronomy (AST113) and biology (BIO100) labs were selected to conduct the initial study. Specific sections were modified and compared with those that did not include the tactile enhancements. Written materials were still made available to BVI students in braille format, but additionally images that related crucial information were converted into a tactile format (Figure 1). For sighted students who participated in the modified labs, both visual and tactile image formats were made available. The study was approved by the institutional review board (IRB), and the approval, which listed all conditions of the study, was filed with ASU. Students who were enrolled in the modified lab sections were informed that enhanced materials would be available, but they could choose whether they wanted to use these in their lab exercise or, if they wished, to be transferred to a standard lab section. All students who participated in these modified labs were asked to sign a disclosure and were notified that all identifying information would remain anonymous.

Transforming images into a tactile format

There are many options for creating 3D tactile images, but the effectiveness of these various formats must be evaluated to determine if the information contained within the image is discernable and if the format of the substrate is safe and sustainable for repeated use. One of the biggest obstacles in converting an image into a tactile format is identifying a simplified image that, when projected in a tactile format, will be discernable and not oversaturated with contrasting details. Generally for lab exercise this is not a concern, because most images used in STEM courses contain line drawings or graphs. For images that have a higher degree of detail, additional steps must be taken to simplify the image while still retaining the educational content. An example of using higher detailed images was encountered when redesigning a taxonomy lab for BIO100. The original lab required students to observe randomly scaled profile images of primates and make observations on structural differences found primarily in the head region. Typically taxonomic differences are made using skeletal remains. In the redesigned version of the taxonomy lab, 2D primate skull images were added, as well as scaled 3D tactile skull images (Figure 2). Use of the skull images not only was the most logical choice for this particular exercise, but also resulted in a more simplified image as opposed to choosing random profile pictures of furry monkeys and converting them into tactile images, which would be very difficult to discern.

Another factor the team had to evaluate was the material and resolution that should be used to create tactile images. Although 3D printers are becoming more widely available, the working area of these printers is usually small, which limits not only the size of the image that is to be converted, but also the space to add

FIGURE 2

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.

braille labeling. Braille standards require specific height and spacing, which creates an additional restriction on images' format size. It is critical to allow sufficient space within an image so that the resolution of the braille font is legible and the height aspect meets acceptable standards. For this study the American National Standard: 2003 Accessible and Usable Buildings and Facilities measurements were used (International Code Council, 2004). These standards require that braille dots be domed and adhere to specific dimensions.

Multiple substrates were tested in creating the tactile images to find the most effective material and lower cost alternatives to duplicate the images. The first materials tested within this project were Corian (acrylic polymer) and medium density fiberboard. These were both found to be poor choices, because Corian creates sharp edges when milled and medium density fiberboards are made of composite materials that can contain chemicals such as formaldehyde, which are not suitable for use that requires routine tactile interaction. CNC (computer numeric code) technology is widely used to create public braille signage such as that used for restrooms, ATMs, elevators, and room signs. For this study, HDP (high-density plastic) boards were selected as the best substrate to use for CNC milling because the plastic can be easily trimmed, is more affordable, has quicker processing times, and has fewer limitations in tactile image size output; also, the surface is resistant to wear, can be easily cleaned, and produces a smooth, high-resolution relief surface.

Image selection

The 3D tactile images enable us to display either a simplistic binary image such as braille, which has only two intensities consisting of black or white, or an image comprised of multiple intensities using variable height. Images that are not line diagrams, graphs, or tables typically contain different levels of shading that in scientific images may correspond to intensity levels or differences in height. The HDP boards were cut such that the highest points represented the brightest element within the picture. For the BIO100 course, mammalian skull images were milled into the boards, and the differences in brightness made it possible to create contours that were similar to that of an actual skull. Major features such as bony protrusions and depressions were clearly defined while maintaining the actual scale for easy comparison (Figure 2). Translating color into a tactile format was a different challenge because the height of the board is set to demonstrate height, intensity, or brightness. To visualize colors, a spectroscopic image was used (Figure 3), which had a color scale written in braille and was etched into an HDP board and arranged with red on the left and blue on the right. To understand the distribution of color in terms of

FIGURE 3

Tactile spectral images enable blind or visually impaired (BVI) students to successfully match sets of unlabeled 3D tactile spectra with corresponding templates during the AST113 spectroscopy lab. Spectral 3D tactile image with atomic elements Hydrogen (A) and Neon (B) labeled in braille are shown next to the actual laboratory spectra image for the corresponding atomic gasses. Wavelength scale is in nm. Images on right courtesy of Joshua A. Barnes (http://www.ifa.hawaii.edu/~barnes/ASTR110L_F05/spectralab.html).

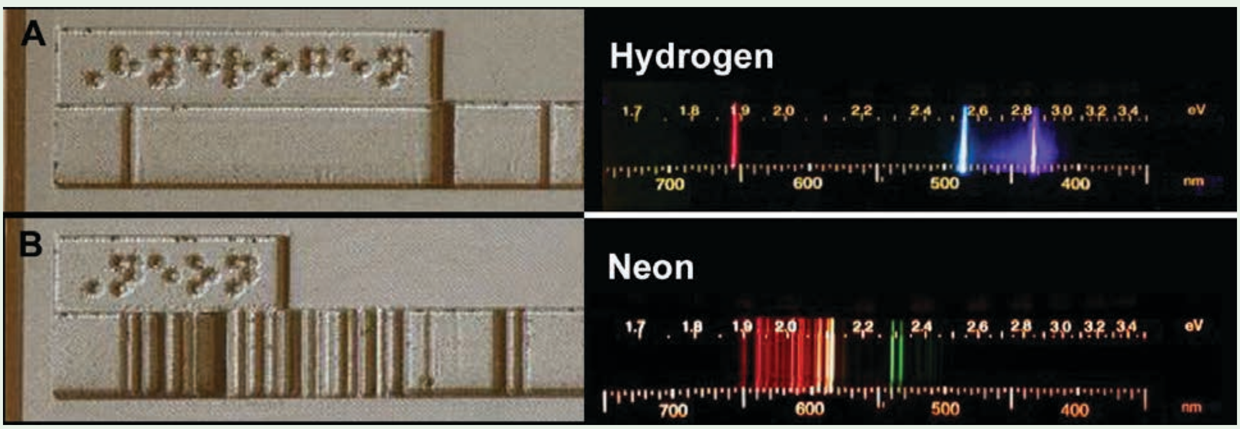
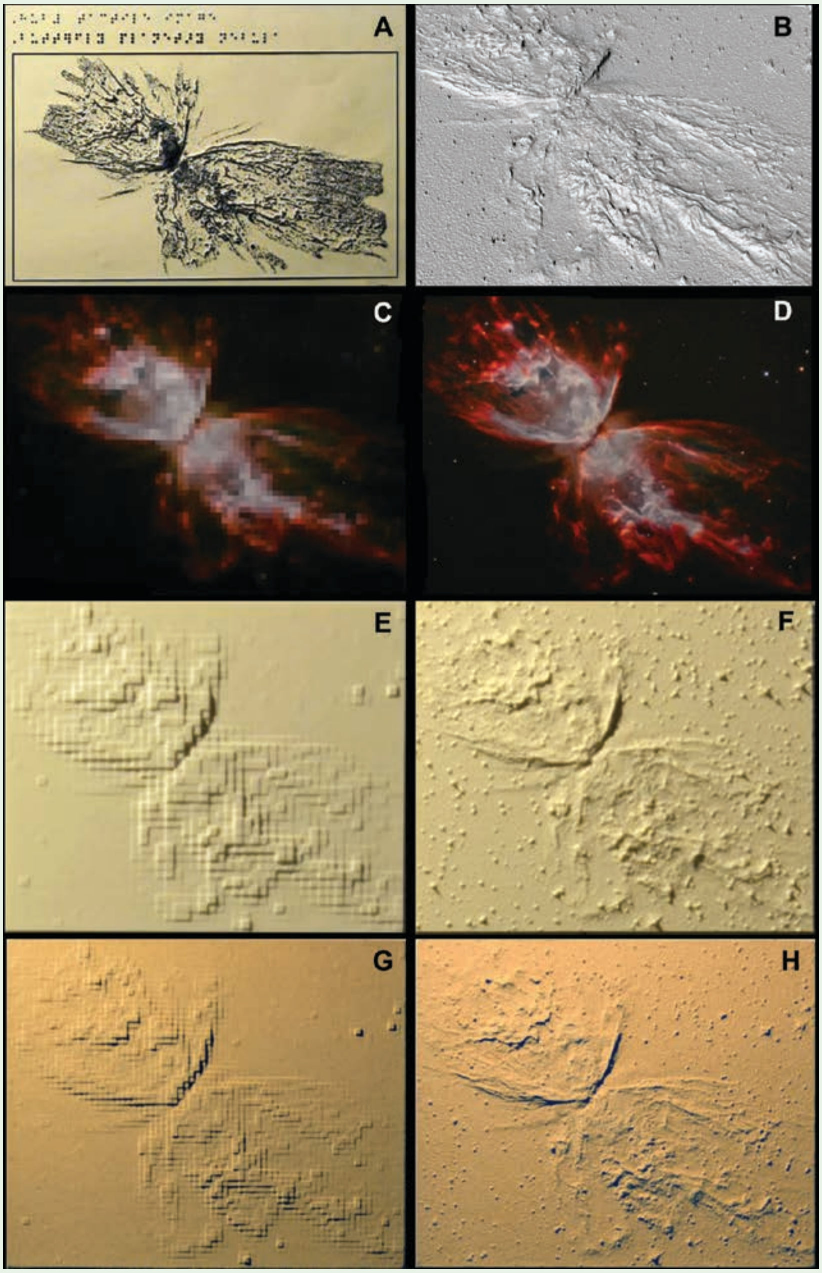


FIGURE 4

Comparison of different substrates and resolution to create tactile images. The Hubble Space Telescope wide field camera 3 Butterfly Nebula image was tested in various formats including raised print (A), HEP (B), low-resolution (C) and high-resolution (D) print, as well as using Corian (E, F) and the medium density fiberboard (G, H) in both low and high resolution (E, G, F, H). The higher resolution images were better able to highlight smaller stars found within the image (image from Mechtley et al., 2012).



a separation based on wavelength or frequencies, students were also given descriptions to help visualize the distribution pattern, such as the space from red to blue representing variations similar to regions of hot and cold water, which contain a gradient in temperature.

Learning styles

Although the 3D tactile formatted tools were intended to assist the BVI students, it was discovered that these materials were also very valuable to the sighted students. All students have differences in their learning styles that require various combinations of visual-, auditory-, and tactile-type formats. Often educational materials will shift to a concentration of visual- and auditory-type formats such as textbooks, lectures, and written assignments as the material becomes more complex. Those who have a visual limitation or are tactile learners can become quickly discouraged. The tactile element allows students to physically conceptualize the material, which is very useful for those with decreased vision. STEM concepts are ideal to be taught using a tactile format because much of the content represents descriptions of physical dynamics or relationships, which are why most of these courses are taught with a lab component.

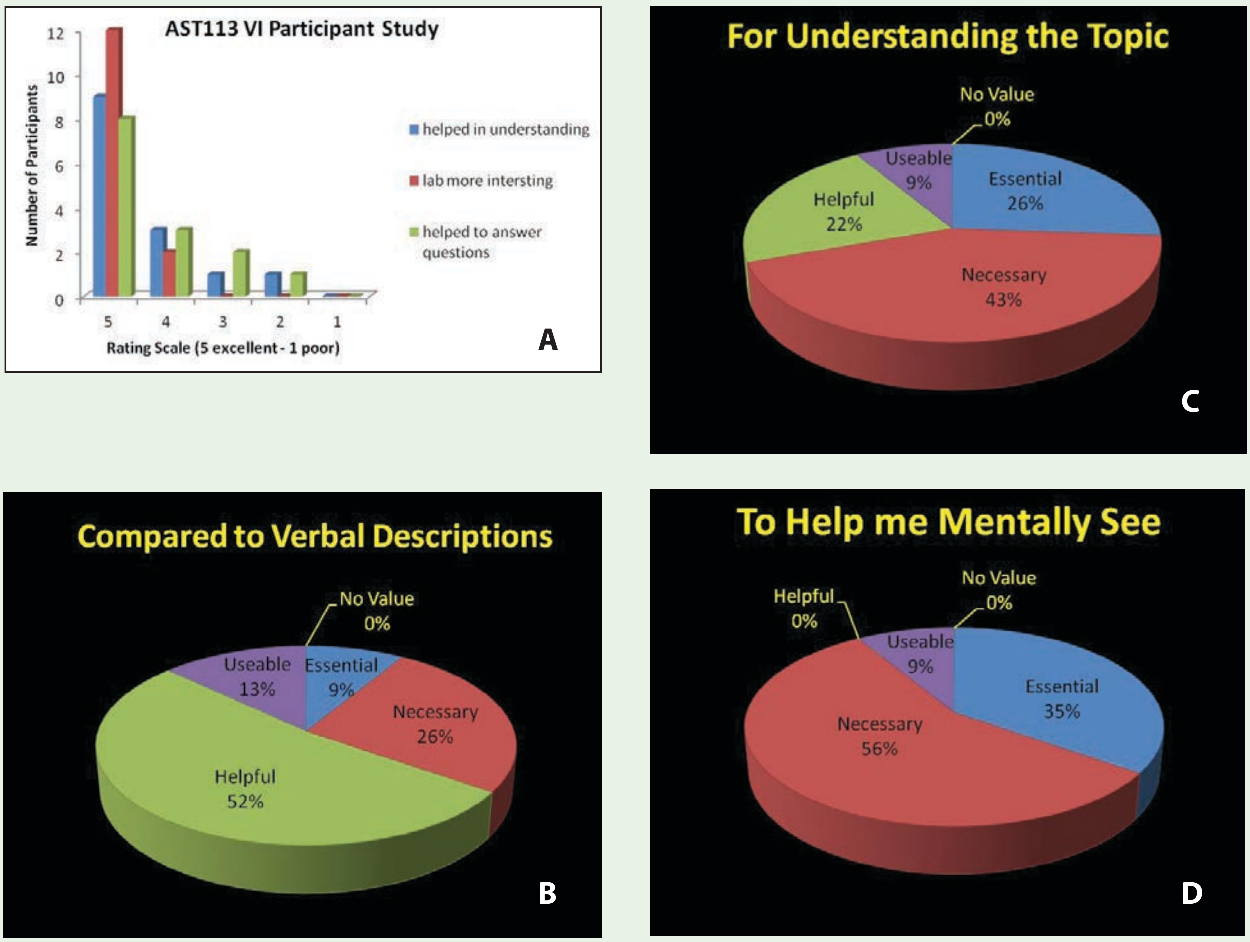
Educators often wonder if instructors should evaluate the students within their class to determine if they are predominantly visual, auditory, or tactile learners and then customize the content to specifically address the needs of the students. Past studies have addressed this question by placing randomly selected students into classroom environments that used either laboratory-type, hands-on lessons or a classroom-type format that only used text. In one study, students were taught chemistry concepts involving molecular structures and were assessed after one week. Students who were taught using the hands-on laboratory setting reported that they enjoyed their lessons much more than their peers, who only participated in the text-based format. When compared on the basis of their retention and understanding, the tactile learners received an average test grade of 95%, whereas their text-based peer had an average test score of 80%. From these reports, it was determined that instructors should not worry about matching learning styles to students, but should understand that some concepts, especially in lab-based disciplines, are best taught using tactile-learning style (Pashler, McDaniel, Rohrer, & Bjork, 2008).

Observations and results

Evaluation of the tactile image boards and activities was conducted within the individual lab sections through

FIGURE 5

(A) Bar chart showing the results of the focus group study that included blind or visually impaired (BVI) students. The study clearly demonstrates the power of our 3D tactile images in helping BVI students understand the lab materials. (B) Pie diagram showing results of the focus group study. The 3D tactile images were considered "helpful-to-necessary" compared with verbal descriptions (by sighted assistants), which is how images are normally conveyed to BVI students in science classes. (C) Pie diagram showing that the 3D tactile images were clearly judged by the focus group study as "necessary-to-essential" to help BVI students better understand the topic. (D) Pie diagram showing that the 3D tactile images were also clearly judged by the focus group study as "necessary-to-essential" to help BVI students mentally envisage the lab images.



surveys and assessments. For this study, the research team consisted of students and staff who all have STEM training and represent individuals with varying disabilities including blindness. The diversity of team members gave invaluable input during the initial design of the 3D tactile images. It was identified through this screening process that images would need to be introduced slowly to BVI students so that they could become adjusted to interpreting information using a tactile image as opposed to only using test or image descriptions. This transition was made using low-resolution images that would be slowly modified to contain more detail. The Hubble Space Telescope Butterfly Nebula was an example of an image that had been created in a high-, medium-, and low-resolution version using HDP boards (Figure 4).

Alternate tactile formats were also tested, because educators who choose to use these tools will soon be faced with providing a sufficient number to accommodate a general classroom size and ultimately storage limitations. The boards were compared with the same image created with a thermal printer, but the student feedback indicated that the thermally printed version didn't provide the same level of detail to give a clear impression of the image. The 3D tactile image was also used to create a thermoform replica, which is a technique of creating an embossed plastic sheet impression. The thermoform sheet had a low level of rigidity and was not as durable for repeated tactile interaction. Although raised print and thermoforms were not as robust as the HEP material, students were still able to interpret the tactile images, so these could in principle be used as substitutes for large classes of BVI students.

On evaluation of the HEP boards, BVI students initially agreed that the high-resolution version was too detailed to discern the subject matter, but after routine use of the medium resolution version, they began to change their preference to a higher resolution. Similar to the study conducted by Pashler et al. (2008), all students who worked with the tactile images had improved participation and performance for the AST113 and BIO100 exercises, but this was especially observed for BVI individuals who had an average 25% improvement of scores compared with students who only used braille text to participate within the same exercise and assessment. Throughout the semester, test scores continued to improve over time for the BVI students as they became adjusted to using the tactile boards.

Participation of BVI students in STEM-based labs is generally less than one percent of registered students at ASU, which is similar to statistics found at other state universities. Such low numbers created a small sample size to adequately base an evaluation of how well 3D tactile images improved the performance of BVI students in entry-level STEM classes. Therefore participation studies were organized to include a group of visually impaired individuals that were recruited from the community as well as from the university. An additional focus group of sighted students from the university was also organized to demonstrate that the inclusion of tactile materials would be beneficial to all students. Sample labs were taken from both the AST113 and BIO100 classes and presented by experienced teaching assistants. Each lab was divided into two parts so that the participant would experience half of the lab exercise with either the inclusion of the tactile image boards or braille (or written) text. These students were then given questions to answer that would assess their understanding of the material.

Results of these participation studies reinforced the conclusions found by Pashler's group and others that adding tactile learning aids will improve the participation and performance of students, and more important, that this was also found true for the visually impaired students. Surveys collected from both BVI and sighted students within the AST113 and BIO100 courses found that none of the tactile images were rated as having "no value" (Figure 5). Additionally, assessment results ranged as high as a 60% improvement for students participating in the focus group study.

Summary

Tactile literacy may become an essential tool in the future to help BVI students pursue higher levels of postsecondary education and ultimately obtain professional employment in STEM fields. It is important that educators continue to develop and test new tactile technologies to make STEM education accessible for individuals who have visual impairment. The 3D-tactile images used in this study were able to help BVI students learn STEM educational content from images, which improved their assessment scores and also was attributed by them to be a major contributing factor to their improved performance. Similar conclusions were found from the participation studies in which BVI students who used the tactile images scored higher than their counterparts who did not. As students continued to use the 3D images, their preference increased to a higher resolution image, which suggests that tactile image literacy is a gradual process that must be slowly introduced. ■

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Eric Hasper (eric.hasper@asu.edu) *is a student in the School of Earth and Space Exploration,* ***Rogier A. Windhorst*** *(rogier.windhorst@asu.edu) is a professor in the School of Earth and Space Exploration,* ***Terri Hedgpeth*** *is an academic professional in the Disabilities Resource Center,* ***Leanne Van Tuyl*** *is a graduate student in the School of Life Sciences,* ***Ashleigh Gonzales*** *is a graduate student in the School of Life Sciences,* ***Brittany Martinez*** *was a graduate student at the time of the study,* ***Hongyu Yu*** *is an associate professor in the School of Electrical, Computer and Energy Engineering,* ***Zoltan Farkas*** *is lead mechanical engineer in the Mars Space Flight Facility, and* ***Debra P. Baluch*** *is an associate research scientist in the School of Life Sciences, all at Arizona State University in Tempe.*