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**Authoring and Assessing Automatically Generated Tactile  
Graphics**

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# **Authoring and Assessing Automatically Generated Tactile Graphics**

**by  
Katherine Clark**

## **Thesis**

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## **Abstract**

# **Authoring and Assessing Automatically Generated Tactile Graphics**

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Images such as photographs, paintings, maps, diagrams, and illustrations are important components in educational, professional, and cultural settings (e.g., photos in a presentation or artwork in a museum). However, access to these images for blind and low vision (BLV) individuals is sometimes lacking since verbal descriptions alone fail to capture in detail the relative sizes, spatial relationships, textures, and other compositional attributes of objects in an image. Tactile graphics are used to present complex visual information contained in 2D images in a more accessible way. However, tactile graphics are not always available as they require specially trained designers to create them and, thus, involve a steep learning curve for untrained individuals who try to make them.

We provide a tool for non-experts to automatically generate tactile graphics. We present a system that allows users to upload a single image to automatically generate a range of tactile graphics options, including outlines for paper embossings, 2.5D or "bas-relief" models for 3D printing, and fully 3D models for 3D printing. Because 3D and embossing printers have become increasingly affordable and accessible through public spaces like libraries and schools, we aim to leverage these technologies as cost-effective alternatives to more expensive mediums (e.g. refreshable tactile

displays, etc.). We conducted user studies to assess both the usefulness of the creation tool and its resulting tactile graphics to better inform future decisions regarding tactile graphics mediums for different image types, as well as the potential for automatic tactile graphics generation in a variety of settings.

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# Chapter 1: Introduction

Two-dimensional images such as photographs, paintings, maps, and illustrations are important means of communication across cultural, educational, and professional settings. As such, proper access to images is important not only to sighted people but also to blind and low vision (BLV) people. Typically, BLV people access images via verbal descriptions (either textual or auditory); however, it is very difficult to fully convey all aspects of a visual composition in a strictly verbal format. Verbal descriptions often omit information related to the relative sizes, colors, spatial relationships, and textures in certain complex images since verbally communicating an image’s compositional attributes in detail would become taxing and likely prove untenable Reichinger et al. (2011). Thus, the issue of proper accessibility of images for BLV people remains an important area of ongoing research.

We explored how tactile graphics are a promising area of research for addressing the limitations of verbal descriptions because they allow BLV people to engage more fully through “tactile exploration” Volpe et al. (2014). Tactile exploration is a process that enables BLV users to generate a more complex mental image via two phases: an initial, rapid pass over the whole, and a second, more refined pass over surface details Volpe et al. (2014). Combined, these two phases allow for greater understanding of details within the full image composition. Additionally, physical interaction has been proven to facilitate memory, problem solving, and understanding; hence, tactile exploration allows users to build richer spatial and conceptual models than verbal descriptions alone might afford Foglia and Wilson (2013).

Recent research efforts have explored how tactile graphics may support greater image understanding across STEM Pineros et al. (2025); Ladner et al. (2005), arts Holloway et al. (2019); Cavazos Quero et al. (2021); Cho (2021), cultural Urcia et al. (2018), and other educational contexts Holloway et al. (2022b). Common tactile mediums include refreshable tactile displays (RTDs) Holloway et al. (2022a), 2.5D

shape displays Siu et al. (2019); Reichinger et al. (2016), 2.5D bas-relief models Reichinger et al. (2011); Cho (2021), 3D printing Holloway et al. (2022b); Neumüller et al. (2014); Jafri and Ali (2015); Reinders et al. (2025), swell paper, embossed paper, and handmade models Gardner (1996), among others. Each of these formats have different advantages and disadvantages, like cost, feasibility, ease of creation, and ease of understanding.

Despite the need for tactile accessibility, creating effective tactile graphics remains a costly and labor-intensive process, which often requires the work of trained specialist designers Ladner et al. (2005). Moreover, there is a steep learning curve associated with the creation and printing of tactile graphics due to the challenge of teaching non-experts how to utilize requisite technologies, like 3D modelling and graphic design software Butler et al. (2021). To address this learning gap, interest in automating all or part of the tactile graphic design process in order to make the creation process more accessible to non-experts has grown in recent years Reichinger et al. (2011); Ladner et al. (2005); Furferi et al. (2014).

Current research has not fully explored how BLV individuals engage with different mediums of tactile graphics and whether certain types of tactile graphics are more effective for specific types of visual content. Preferences for embossed outlines, bas-relief reconstructions, and full 3D models may vary, depending on the complexity and context of each image (e.g., would a fully 3D model or an embossing be more effective for communicating a photograph of a person?). Additionally, the impact of imperfections in an automatically generated tactile graphic remains unexplored (e.g., is it possible that inaccuracies in depth estimation or hallucinations in machine-learning-generated 3D models negatively affect user comprehension or experience?).

Thus, we have developed a prototype of a tactile graphics creation tool that generates multiple mediums tactile graphics at once based on the same input image (outlines for embossing, a bas-relief model, and a 3D model). The focus of our research includes two related studies: 1) an exploratory authoring study using our creation

tool with people who work with, teach, and/or provide accessibility services to BLV people, and 2) a tactile medium comparison study with BLV people.

The interpretation pilot study explored the preferences of BLV people when interacting with tactile representations of 2D images, including embossed outlines on paper, 3D printed bas-relief (also called 2.5D) reconstructions, and 3D printed “in-the-round” (fully 3D) reconstructions. Study participants assess these tactile translations of a set of images and provide feedback on each image type and for each medium.

The results of this study give us valuable insight into whether there are preferences of mediums of tactile representations of complex imagery overall, as well as preferences within each image category (diagrams, architecture, photography, naturalistic art, and abstract art). Based on the user study, we also determined the utility of existing tactile graphics translation methods based on user responses to their printed results. These results can inform future design decisions regarding tactile graphics for complex 2D images in both educational and museum/gallery settings.

## Chapter 2: Related Work

### 2.1 Tactile Graphics in Humanities Education

Tactile graphics have traditionally been used to support access to STEM content as diagrams and charts are often more easily translated into tactile form Butler et al. (2021); Ladner et al. (2005). These graphics tend to be linear and much more straightforward, making them more suitable for simplified tactile representations, like embossed paper or braille descriptions Pineros et al. (2025). However, access to tactile graphics in humanities education—where content often includes photographs, artworks, and maps—remains comparatively underexplored Butler et al. (2021). Such images present unique challenges due to their visual complexity, subtle spatial relationships, and rich compositional attributes, which are difficult to convey through verbal or braille descriptions alone Reichinger et al. (2011).

Prior work highlights the limitations of descriptive alternatives, noting that audio guides and braille descriptions often impose a fixed interpretation of an image, constraining a BLV individual’s agency in forming an independent understanding of the image at hand Reichinger et al. (2011). BLV individuals have also expressed dissatisfaction with 2D tactile translations of 3D objects (i.e., images of 3D objects) and 2D representations of complex images, particularly in how depth is represented in paper embossings with intersecting lines Zebehazy and Wilton (2014). These limitations point to a need for more expressive tactile representations, such as bas-relief or fully 3D reconstructions. However, as noted by Reichinger et al., the translation from 3D to 2D representation is non-trivial as hidden sections and the “back” of images must be either manually recreated or hallucinated Reichinger et al. (2012).

## 2.2 Tactile Graphics in Cultural Spaces

There is growing recognition of the value tactile graphics can bring to art and cultural spaces. Studies show that BLV museum visitors prefer multisensory and touch-based exhibits Handa et al. (2010), and some institutions have adopted tactile models to improve accessibility Butler et al. (2021, 2023). However, these models are typically handcrafted by experts specifically for each exhibit and are, therefore, costly and time-consuming to produce, making them impractical for temporary exhibitions and/or classroom lectures. Similarly, commissioned reproductions and casts of museum artifacts for tactile use are also cost-prohibitive, and, therefore, not widely accessible. This has led to increased interest in digital fabrication techniques in museum spaces Butler et al. (2023); Neumüller et al. (2014); Scopigno et al. (2014), as well as greater research into automation as a potential way to scale tactile graphic creation for broader applications.

A recent project, “A Gallery In My Hand,” explores tactile access to visual art by manually creating tactile versions of artworks for exhibition Butler et al. (2023). While this project affirms the demand for tactile graphics in the arts, it relies on handcrafted graphics and does not explore scalable or automated solutions. Other projects also provide support for generating tactile graphics from visual art but are limited by genre of the work (e.g. single-point perspective), long processing times, and do not explore the possibility of image to 3D model conversion Furferi et al. (2014); Reichinger et al. (2011); Volpe et al. (2014); Governi et al. (2014).

## 2.3 Automated Approaches to Tactile Graphics

There has been an increase in automated and semi-automated approaches to tactile graphic generation Reichinger et al. (2011); Ladner et al. (2005); Furferi et al. (2014). However, some of these tools often assume the availability of design expertise or access to specialized software, thereby limiting their utility for teachers or museum professionals without design backgrounds Butler et al. (2021). Ladner et

al.’s early work, for example, automates certain aspects of tactile graphic generation while targeting trained tactile graphics designers rather than empowering non-experts to create their own Ladner et al. (2005).

The application of machine learning (ML) to the translation of visual images to tactile graphics has become more common in recent years. This emerging technology uses monocular depth estimation that allows for the reconstruction of an approximated bas-relief or fully 3D mesh version of an input image, which can then be 3D printed. This approach follows the findings of Klatzky et al. (1993) in which the authors discuss the preference of "real objects" over 2D representations due to the presence of "additional kinesthetic information" in the form of higher dimensionality (depth). However, these ML tools still result in imperfect recreations, especially when only one view of an image subject is available (as is the case when attempting to translate works of art and/or humanities-related images into tactile models).

## **2.4 Methods of Tactile Graphics Generation and Limitations**

3D printing has emerged as a promising medium for tactile accessibility due to its customization ability and declining costs. Holloway et al. used 3D printed kits to support orientation and mobility (O&M) training for BLV youth by modeling different street crossing scenarios Holloway et al. (2022b) while Puerta et al. investigated the optimal 3D printing orientations for braille readability, contributing valuable insights for producing high-quality, 3D-printed tactile materials Puerta et al. (2024). These studies demonstrate the potential of 3D printing to produce affordable, effective tactile learning materials. Phutane et al. found that educators prefer 3D models of real-world objects for teaching despite the difficulties in creating them, reinforcing the need for tools like 3D-printers and automatic model generation software, which can reduce the tactile graphics production burden Phutane et al. (2022).

Alternative approaches to tactile graphics production include machine embroidery and refreshable tactile displays (RTDs). Seehorn et al. automated the generation

of embroidered tactile graphics using custom stitch patterns based on visual contrast and continuity analysis Seehorn et al. (2022). However, their work focused exclusively on charts, maps, and diagrams, resulting in questions about how best to represent more complex imagery. Holloway et al. used RTDs to display motion graphics, but the displays’ low resolution and high cost limited their broader applicability Holloway et al. (2022a).

While prior work has expanded access to tactile graphics, these existing methods often rely on specialist knowledge, focus narrowly on STEM content, and/or lack scalability. Our project addresses these gaps by providing a tool for generating tactile graphics from a single 2D image and is designed specifically for non-expert users. By offering multiple output formats (embossed outlines, 2.5D bas-reliefs, and full 3D models), we aim to support diverse use cases in educational, cultural, and everyday contexts. Our approach also builds on recent developments in machine learning, particularly monocular depth estimation, to approximate the depth and spatial relationships necessary for effective tactile translations. In doing so, we contribute a scalable, low-barrier alternative to tactile graphic creation that expands access beyond STEM applications into the domains of the arts and humanities.

## Chapter 3: System

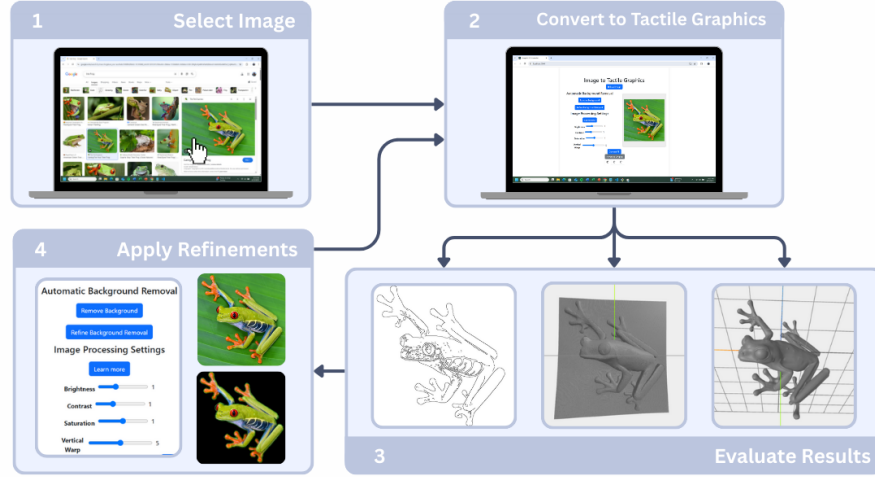


Figure 3.1: Our creation tool allows users to automatically generate a range of tactile graphics, including: outlines for paper embossing as well as 3D-printable bas-relief (2.5D) and fully 3D models from a single image. The flowchart above illustrates the workflow of selecting an image of the user’s choice, uploading it to our creation tool, applying necessary image processing options, and iteratively evaluating their results.

Our goal was to implement a system that automatically generates three separate, downloadable tactile graphics from a single, user-uploaded image to facilitate tactile graphics creation. Users can choose to apply different pre- and post-processing effects to their image and are then able to generate outlines for paper embossing, and 3D-printable bas-relief and fully 3D models.

To create a prototype of our image to tactile graphic tool, we implemented a React web application 3.2 with a connected Flask backend. This enabled us to use OpenCV’s Canny edge detection algorithm Canny (1986); Bradski (2000) to create embossing outlines, DepthAnythingV2’s Yang et al. (2024) depth estimation pipeline to generate the bas-relief meshes, and the TripoSG Li et al. (2025) model to generate 3D models.

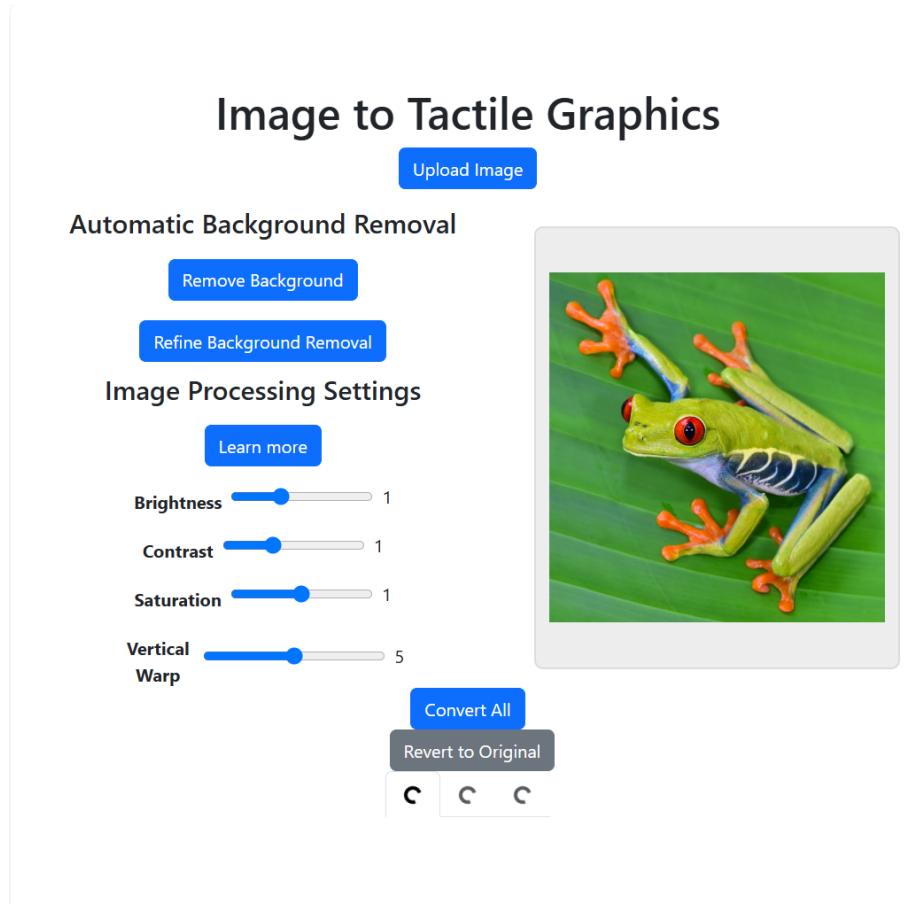


Figure 3.2: A screenshot of the web application before a user clicks the "Convert" button to generate their tactile graphics.

### 3.1 Image Processing

Our system allows for users to apply various image processing options to enhance the input image before depth estimation and 3D reconstruction, including: sliders for brightness, saturation, contrast, and vertical warp, as well as tools to remove the background of an image.

1. **Brightness:** Areas of brightness in an image can be interpreted as textural detail and can also be used to find boundary or contour lines within an object Martin et al. (2004). By allowing users to increase the brightness of dark images, they are able to achieve a higher level of detail in the final tactile graphics.

2. **Contrast:** A balanced contrast level improves the differentiation between an image's light and dark areas, making the boundaries of the objects in the image more distinct. The results of O'Shea et al. (1994) and Egusa (1983) note that the apparent depth of an object is more dependent on the relative contrast of the objects than its absolute luminance. By allowing users to increase contrast, we ensure greater variation of surface height in depth reconstruction and more distinct contour lines in edge detection.
3. **Saturation:** Findings on the relationship between object colors and depth perception suggest that objects of different colors at the same physical distance can appear at different depths, depending on the color of their surroundings Egusa (1983). Desaturating an image before converting it to a tactile graphic can help to mitigate these effects, allowing depth to be inferred from contrast in light and dark regions rather than from hue variations.

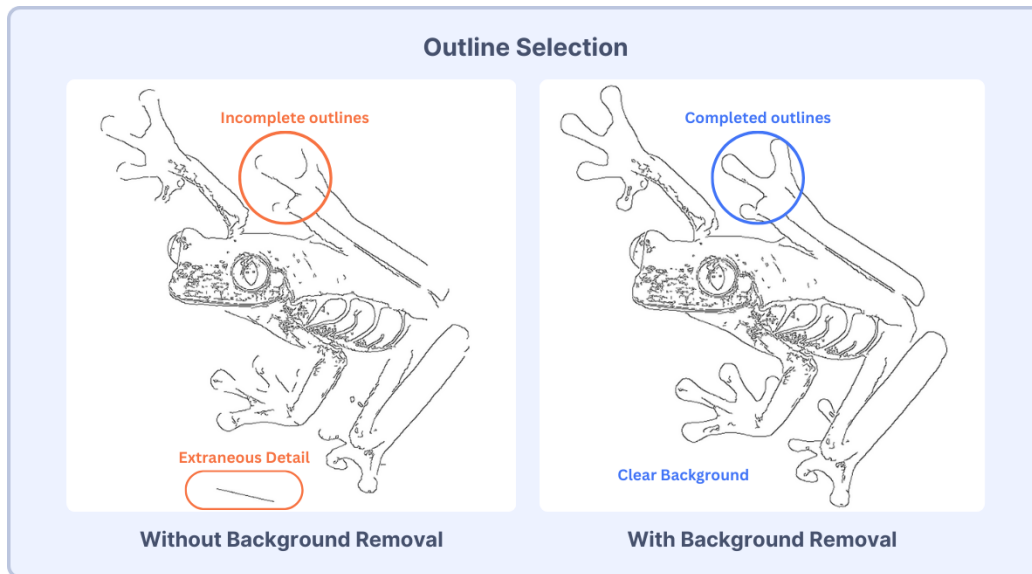


Figure 3.3: A comparison of the results of edge detection with (right) and without (left) background removal. In the left results, outer edges are much less defined and there is a greater presence of irrelevant edges. In the right results, outer edges are closed and less irrelevant edges are present.

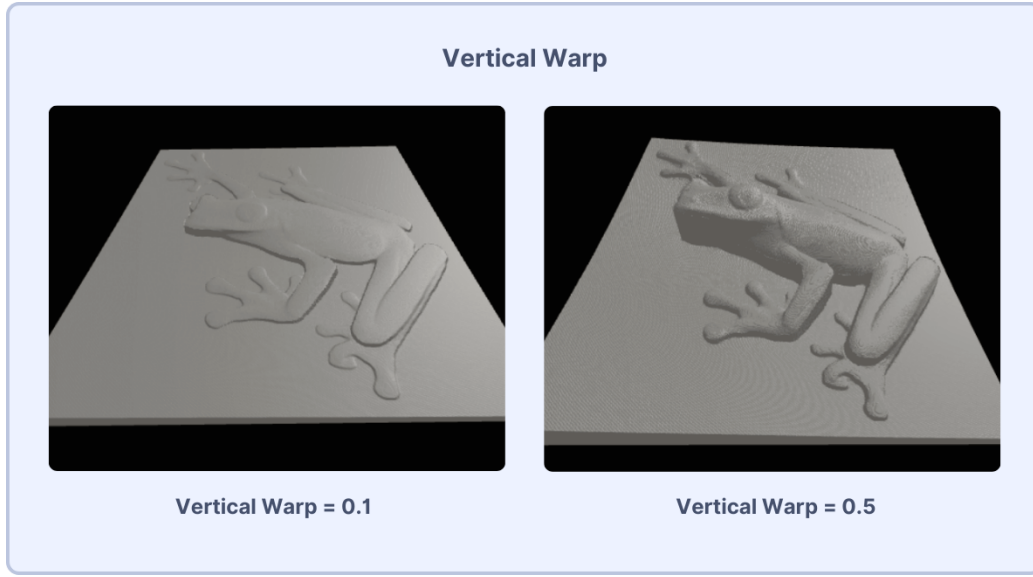


Figure 3.4: A comparison of the results of selecting a value of 0.1 (left) versus a value of 0.5 (right) for vertical warp. The greater value of vertical warp results in much greater variation in depth for greater appearance of realism in the final output.

4. **Background Removal:** Background removal is essential for isolating the subject of the user’s uploaded image. This step is especially important for images with significant background “noise” (e.g., other people in the background of a portrait), which could introduce unwanted details in generated tactile graphics 3.3. Our implementation utilizes the Rembg Gatis (2020) library to automatically segment the subject of an image from its background. We also provide users with the ability to make pixel-level refinements with a “brush” tool where they may either black out or reapply original pixel colors. The brush tool uses mouse interactions on an HTML canvas element to either draw on the original pixel colors in “erase” mode or black out pixels in “draw” mode.
5. **Vertical Warp:** One issue we encountered during initial testing was occasional flatness of bas-relief representations 3.4. To rectify this, we added a parameter to warp the output of the depth estimation to create exaggerated results for a higher degree of texture and depth. As depth values may vary from image to

image, we first normalize the values of the depth map on a scale of zero to one. We can then compute a scaler value based on the user’s selection of the vertical warp value and the existing range of the depth map. Finally, we scale the depth map in proportion to the depth variation of the original inference while still exaggerating the texture of the output.

### 3.2 Embossing Outlines

The implementation for creating outlines of a user’s uploaded image for paper embossing relies heavily on edge detection. By identifying the contours of objects in an image, we can generate clear outlines of important features that should be present in the final tactile graphic.

Edge detection identifies areas in an image where there is a significant change in pixel intensity, which is assumed to be a boundary line between objects in the image or discrete parts of the same object (e.g. separating the subject from the background or defining an eye on a face).

In our implementation, we use OpenCV’s Canny edge detection algorithm Bradski (2000); Canny (1986). This algorithm is controlled by two threshold values that define the sensitivity of the edge detection. The first threshold controls the lower bound for edge detection with any change in intensity higher than this threshold immediately being considered a ”sure-edge.” The second threshold controls the upper bound for edge detection, meaning it defines the maximum value of an intensity change that can be considered a weak edge. In this algorithm, sure-edges are always added to the final output while weak edges are only added if they are connected to a sure-edge.

The output of this process is then converted to a PNG image format with black outlines on a white background for use in paper embossing with a Cricut Maker.

### 3.3 Bas-Relief

The implementation of bas-relief (or 2.5D) translation from a user’s uploaded image requires the use of a monocular depth reconstruction machine learning model to infer the depth of each pixel in an image. We chose to integrate the DepthAnythingV2 model Yang et al. (2024) due to its high level of detail retention and its availability as a pre-trained model.

The output of the model is a depth map containing information on the perceived distance from the camera of each pixel in the image. To be able to translate this depth information into a proper mesh, we first normalize the depth values between zero and one to allow for vertical scaling. This is the point in the process where we apply the information from the user’s choice of **vertical warp** to either exaggerate or dampen the depth of the mesh. We then ensure that the depth map aligns properly with the original image before continuing to assemble the vertices and faces of the mesh.

The first step in generating the mesh is to create the top face where the height of each vertex corresponds to the depth map value of each pixel. Next, we add a single flat face beneath the textured top face to serve as the back panel of the graphic. Finally, we construct side walls of the graphic by connecting adjacent vertices on the top and bottom faces.

The resulting 2.5D mesh is then exported as an STL file to be available for 3D-printing.

### 3.4 3D Model

The process of creating a 3D model from a user’s uploaded image uses the TripoSG Li et al. (2025) model. TripoSG was chosen as it has an available open source code base and the ability to generate a high quality 3D-printable model from a single input image.

We pulled the necessary files from the TripoSG GitHub repository into our project to handle image-to-3D conversion. TripoSG requires a single input image and an output destination to generate a 3D model. After creating an output directory, we are able to run a manual inference on the submitted image with a subprocess shell command.

Finally, we convert the resulting GLB format mesh to an STL file using the Trimesh Dawson-Haggerty et al. library’s export feature to ensure compatibility with standard 3D printers.

### 3.5 Previewing Tactile Graphics

After the user is satisfied with their image processing selections, they are able to convert their chosen image into all three tactile graphic types at once. Previews of each are available at the bottom of the screen under tabs marked "Embossing," "Bas-Relief," and "3D Model." Each tab also has the option for the user to download their tactile graphic(s).

Because proper thresholds for edge detection vary from image to image, we provide users with three preset outline results with a range of edge detection sensitivity to allow them more flexibility when choosing which output best represents their input image.

While the embossing outline tab simply displays an image preview, the bas-relief and 3D model tabs have interactive previews implemented with three.js Cabello (2010). These two previews allow the user to rotate and zoom in on their generated models to better assess their output.

### 3.6 Printing Methods

Prior to hosting the user evaluation sessions, we printed 21 tactile graphics (seven embossed paper, seven bas-relief, and seven 3D models). We created emboss-

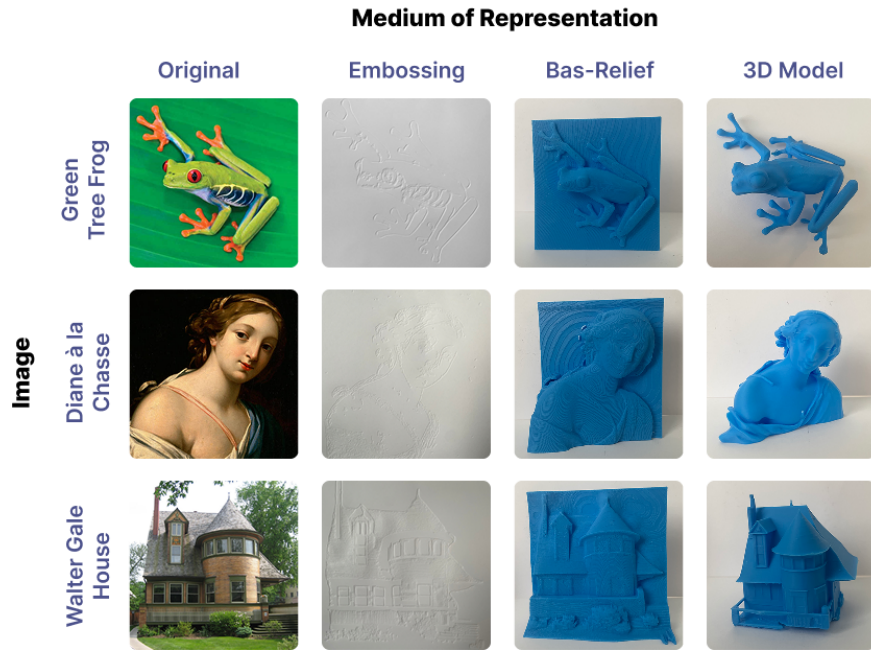


Figure 3.5: Above are three examples of printed tactile graphics generated with our creation tool, including embossed outlines on cardstock, 3D printed bas-relief models, and 3D printed fully 3D models.

ings with the Cricut Maker 3’s debossing tool on heavyweight cardstock, and we made the bas-relief and 3D models using a Bambu A1 Mini 3D printer with PLA filament on a high quality print setting.

All the tactile graphics that were evaluated during the user study sessions were generated with our tool.

### 3.6.1 Paper Embossings

To achieve the final printing strategy for paper embossings using the Cricut Maker 3’s debossing tip, we tested three different methods of creating texture on paper. For all three methods, we first upload the resulting outline image to the Cricut Maker Design Space application and select the ”single layer” option in order

to recognize all outlines.

1. Within the design space, we selected the outline and changed the maker setting to "Deboss." Using the highest pressure option on 100 pound heavyweight cardstock on top of a Cricut cutting mat, we were then able to create debossed lines.
2. Within the design space, we duplicated the outline. Selecting one outline, we created a rounded "offset" edge with a value of 0.05 to create extra space surrounding the outline itself. Making sure that the outline and the offset were aligned properly, we changed the maker setting to "Deboss" on the outline itself and to "Cut" on the offset. Using normal pressure with the Cricut Maker's cutting tip, we first cut out the offset selection on 100 pound heavyweight cardstock on top of a Cricut cutting mat. We then removed the offset area so that there was no cardstock where the outlines would later be drawn and regions between outlines did have cardstock. This allows for the ability to create deeper embossed lines in the final graphic. We then taped or glued a second piece of 100 pound heavyweight cardstock on top of the first (still on the cutting mat). Using a high pressure setting and the debossing tip, we were then able to create deeper debossed lines.
3. Within the design space, we selected the outline and created a rounded "offset" edge with a value of 0.05. We then changed the maker setting "Cut." Using normal pressure with the Cricut Maker's cutting tip, we first cut out the offset selection on 100 pound heavyweight cardstock on top of a Cricut cutting mat. We then removed the offset area so that there was no cardstock where the outlines would be. Finally, we glued the resulting cardstock pieces to a second sheet of paper to create a paper cutting that depicted separate raised areas of the image.

In our interpretation study, we opted to use the second creation method as it produced the deepest embossed lines.

### **3.6.2 3D Prints**

All bas-relief and 3D models that are exported by our tool are in STL format. Because of this, we were able to directly upload resulting meshes to the Bambu Studio application to prepare for printing. Aside from the default settings within the application, we used the following print settings:

1. **Layer height:** 0.1 mm
2. **Initial layer height:** 0.2 mm
3. **Sparse fill density:** 10%
4. **Enable support**
5. **Support type:** Tree
6. **Support threshold angle:** 20°

## Chapter 4: Authoring Study

We held user study sessions with sighted professionals from the arts, education, and museum communities to collect their feedback on the usability of automatically generated tactile graphics in their respective fields.

The user studies were each one hour long, conducted in a one-on-one session either over Zoom or in person and approved by our institution’s Institutional Review Board (IRB). We compensated individuals \$40 each for their time.

For documentation purposes, we screen recorded the creation tool as it was being used by the participants and also captured the audio during each study. We then transcribed all participant comments and completed thematic analyses of responses as they relate to our research questions.

| Authoring Study Participant Information |     |        |                                    |                                            |                                      |              |                                                                    |
|-----------------------------------------|-----|--------|------------------------------------|--------------------------------------------|--------------------------------------|--------------|--------------------------------------------------------------------|
| ID                                      | Age | Gender | Vision                             | Occupation                                 | Experience Creating Tactile Graphics | Frequency    | Preferred Mediums                                                  |
| 1                                       | 54  | Female | Sighted                            | Natural History Museum Program Coordinator | None                                 | N/A          | N/A                                                                |
| 2                                       | 50  | Female | Sighted                            | Teacher of BLV Students                    | 15 years                             | Occasionally | Handmade materials; paper and art supplies, felt board             |
| 3                                       | 50  | Female | Sighted                            | Teaching Assistant of BLV Students         | 7 years                              | Monthly      | PIAF machine, swell paper                                          |
| 4                                       | 31  | Female | Sighted; Convergence Insufficiency | Teacher of BLV Students                    | 7 years                              | Monthly      | Dependent on content; PIAF machine, handmade models                |
| 5                                       | 47  | Male   | Sighted; High Myopia               | Teacher of BLV Students                    | 16 years                             | Weekly       | Dependent on content; graph and peg boards, paper and art supplies |
| 6                                       | 30  | Female | Sighted                            | Art Museum Assistant Curator               | None                                 | N/A          | N/A                                                                |

Table 4.1: Demographics of authoring study participants.

### 4.1 Research Questions

- **RQ1:** How usable and effective is an automated tactile graphic creation tool for non-expert use?

- **RQ2:** How do non-expert users evaluate preferences between different tactile mediums when assessing the clarity of tactile graphics based on different image types?
- **RQ3:** What opportunities and challenges exist in integrating automatically generated tactile graphics into museum and educational spaces?

## 4.2 Method

In these study sessions, participants were asked demographic and background interview questions regarding their visual ability, as well as their prior experience with creating and using tactile graphics 4.1.

Participants were then asked to choose images from a variety of 14 images (categories included architecture, realistic art, abstract art, nature photography, and museum artifact photography). Then, they were instructed to select their desired image processing choices and create a set of tactile graphics. They were also given the opportunity to iterate on their designs by altering their image processing selections and regenerating their tactile graphics until they were satisfied with their results.

After creating their tactile graphics, we held unstructured interviews to ask study participants about their impressions of the creation process using the tool, as well as their impressions of the final tactile graphics that were produced.

## 4.3 Results

### 4.3.1 Participant Background

Four of the six authoring session participants had prior experience in designing tactile graphics 4.1. These four participants were all directly involved in teaching visually impaired students either as a teacher or a teaching assistant.

When asked about time spent creating tactile graphics, this study group described a range from utilizing the most simplistic creation methods to more time-

consuming methods. For example, creating raised line drawings with an embosser may only take 15-30 minutes to produce, but creating more complicated imagery using either software or hand-making was reported to be significantly more time consuming.

**Participant 2:** The majority of P2's experience with creating tactile graphics was with hand-making representations of existing technology, like computer screens and iPad layouts, for her accessible technology courses using paper and art supplies and/or occasionally with an embosser. P2 remarked that she often prefers to use "random supplies" to create 3D manipulatives for her students rather than creating traditional paper tactile graphics.

When you're using a 3D object in some way and manipulating it in some way, sometimes it's easier for [students] to understand than when you're presenting a raised image because tactile graphics historically haven't been great. (P2)

**Participant 3:** Rather than using tactile graphics creation software, P3 typically creates her tactile graphics by using tactile graphics kits that allow her to score or perforate paper to create raised line drawings. She has also frequently used a Picture in a Flash (PIAF) machine to generate raised line drawings with swell paper.

**Participant 4:** Similarly, P4 frequently uses a PIAF machine with thermoform to create her own raised line drawings. P4 also creates tactile graphics by hand using foam and other materials to convey different textures. She noted that when determining how to best represent an image, she searches for material(s) that best reflect the content of the image to provide students with the most faithful interpretation possible.

It sort of depends on what we're trying to create or represent ... any time you use, like, an authentic material that truly matches what you're trying to represent is the best in my opinion." (P4)

**Participant 5:** As a math instructor, P5 most often uses graph and peg boards for concept development. He also creates tactile graphics by either drawing on micro-encapsulated paper, by using a Draftsman tactile drawing board, or by using word processing software to generate graphics that include braille. P5 noted that he considers the ages and tactile comprehension levels of his students when determining which material is best to communicate important concepts. For instance, he described using "craft-based" supplies to create graphics, like "creating bar graphs or line graphs with sticky dots and art tape or foam pieces," especially when working with younger students.

My preference is to go with materials that [my] students prefer ... [then] build on their skills from there and [later] introduce different materials so that they're able to build their tactile discrimination. (P5)

#### **4.3.2 RQ1. Automating the creation of tactile graphics is useful and effective.**

##### **4.3.2.1 User Friendliness**

All participants felt that the creation tool was user-friendly 4.1. P3 remarked that the tool was "easy enough that, truthfully, it could be done by a teacher or a parent in the classroom without having to be sent off [to a specialist]," supporting the idea that automatic tactile graphics generation facilitates easier creation for non-experts. For instance, P1, who had no experience in creating or designing tactile graphics felt that using the tool "was very easy and very simple ... you didn't have to do anything— you just uploaded an image and [the tool] did it for you."

##### **4.3.2.2 Addressing Lack of Training**

Two participants (P3 and P4) noted that the automatic tactile graphics creation tool could be utilized in outreach efforts with local school districts to promote tactile graphics generation for non-expert teachers and teaching assistants.

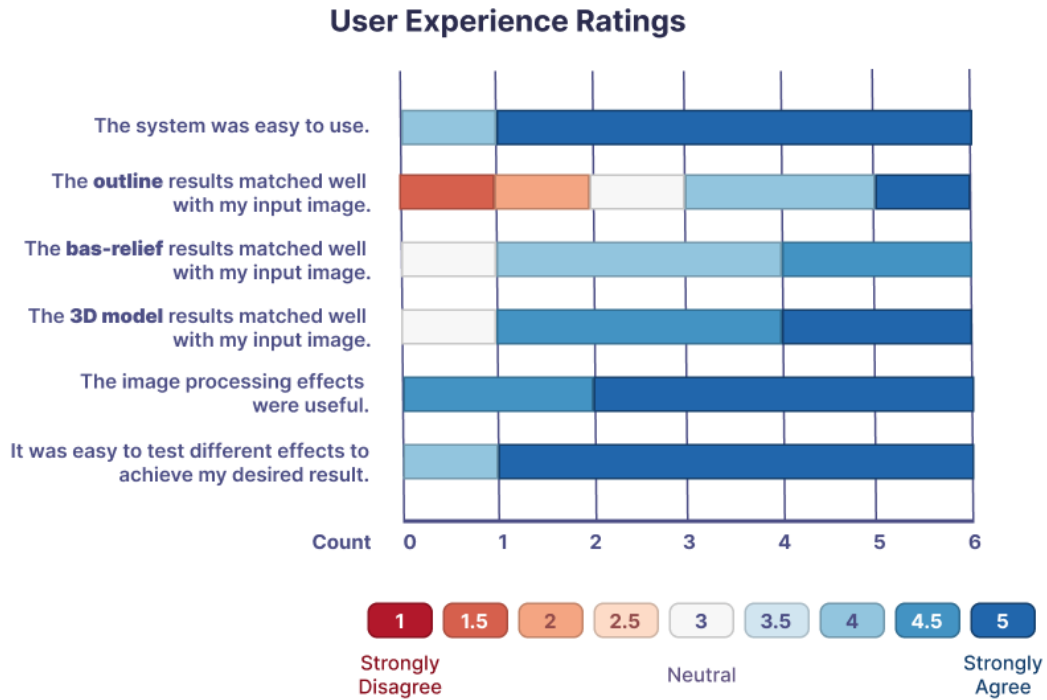


Figure 4.1: Likert scale user experience responses. All study participants rated statements regarding ease of use, quality of results, and usefulness of image process effects highly. The only notable exception were their individual ratings of the quality of the embossing outline results, which were mixed.

Furthermore, P2 remarked that "there's not a lot you have to learn before you can just start playing around with [the tool], and that is a bonus. And then [there's the] ... immediate feedback of what [each tactile graphic] would look like in the different contexts ... those things stood out to me as pluses." Her feedback supports the use case of automatic tactile graphics as a means of lowering barriers for non-expert authors.

#### 4.3.2.3 Helpful In-App Tools

All participants rated the image processing tools highly both in terms of general usability, as well as in terms of making it easier to achieve their desired results.

Among the image processing tools provided, background removal/refinement and vertical warp were the most popular.

Background removal proved to be especially useful in the iterative design process. For example, after describing her initial embossing outline results as "a bit distracting" due to excessive texture, P4 used both the background removal and the refinement tools to eliminate unnecessary detail:

I think it's an improvement for sure. Yeah, I think you could definitely go back in and use [the brush refinement] tool until you have the outlines of the structures you want. (P4)

Similarly, P3 noted that the most useful image processing tool was having the ability to "[go] back and [clean] up the original image ... removing the non-essential parts, like ... background and things we didn't care as much about."

Several participants had mixed responses to brightness, saturation, and contrast adjustments. P5 mentioned that the presence of these options in tactile graphics design software aligned with his previous experience, he was unsure of how much impact changing the values had on bas-relief and 3D models. All participants expressed that they needed more time to manipulate the tool in greater depth to determine the best use cases for brightness, saturation, and contrast.

Study participants responded positively to vertical warp in cases where detail was limited, using it to provide more tactual feedback in the form of depth variation. P5 experimented with a combination of increased contrast and increased vertical warp to enhance the texture of a bas-relief model, noting that the resulting details were more "prominent" than in the initial generated result.

#### **4.3.2.4 Compatibility with Existing Tools**

P3 and P4 stressed the importance of tactile graphics generation tools ideally being compatible with existing tools and workflows at their institution. Both mentioned that in addition to embossing machines, their campus has 3D printers available

for use. P1 also commented that her museum’s creative services department also has a 3D printer available but that “no one’s really used it.”

This is important in terms of addressing the cost-prohibitive nature of tactile graphics generation and requisite materials. Participants liked that our creation tool would be compatible with existing resources at their specific organizations.

#### 4.3.3 RQ2. Preferences between different mediums is largely dependent on context.

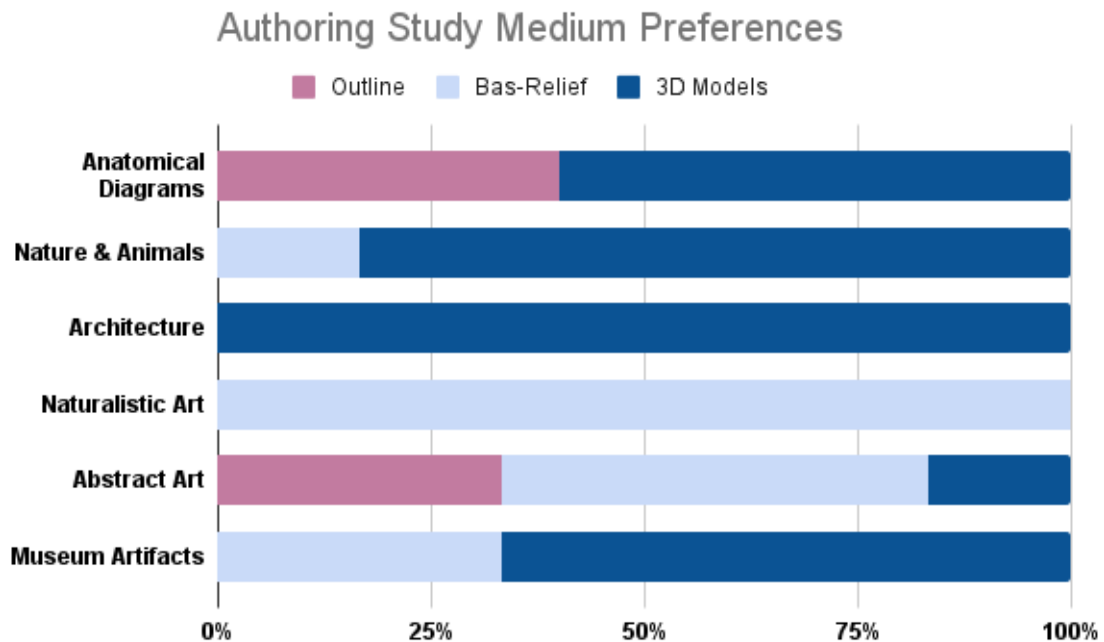


Figure 4.2: Percentage of preferred tactile graphics representation mediums for each presented image category. Overall, 3D and bas-relief models were strongly preferred to embossing outlines. The most divisive image classification was abstract artwork where participants had a more difficult time determining which medium best conveyed the image’s visual content and the artist’s intent.

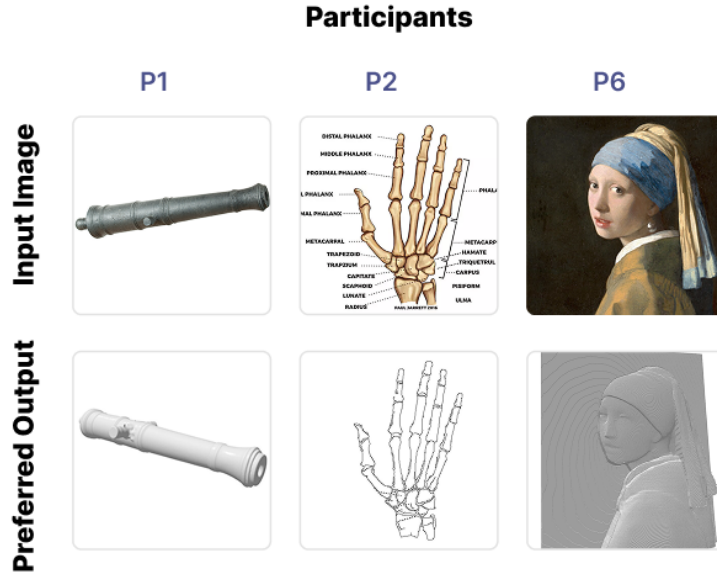


Figure 4.3: Above are three examples of context-dependent preferences when participants selected a resulting tactile graphic. P1 preferred the 3D model representation of an artillery cannon from her institution as it was the most realistic. P2 preferred the embossing outline of an anatomical diagram of the human hand as it gave the clearest distinctions between each bone. P6 preferred the bas-relief representation of the *Girl with a Pearl Earring* portrait, explaining that the bas-relief was faithful to the artist’s intent while still providing greater textural feedback than an outline.

#### 4.3.3.1 Context Dependence

A key finding from all authoring sessions was that the user’s final choice of tactile graphic medium varied greatly depending on intended usage and context—with such variables as BLV student/patron age and existing comprehension level, course/exhibit subject matter, and image category carrying the most weight in the user’s decision. Participants who are Teachers of Students with Visual Impairments (TSVIs) particularly emphasized the importance of being able to customize their creation approaches as students may have varying levels of spatial awareness or prior experience using tactile graphics, which can impact the tactile representation (or

combination of representations) that best expresses a desired learning/interpretation outcome.

The faithful rendering of the resulting tactile graphic with respect to the object or image being represented was the most important factor cited by users in selecting their preferred result from the three available tactile mediums. However, study participants qualified their resulting selections based on their own knowledge of the intended audience’s familiarity with the image’s content, as well as with tactile graphics, in general.

#### **4.3.3.2 2D Representations Preferred for 2D Subjects**

All users in the study agreed that embossing outlines or bas-relief models of two-dimensional works of art were preferable to 3D models. Participants cited various reasons: artist intent, potential confusion for blind students/museum patrons who may incorrectly assume a 2D art piece is a sculpture, and the expectation that a 2D image should be represented in a 2D tactile format.

It’s weird to see [the artwork reproduced] out away from the canvas ... Because it is a painting, and it’s not like a sculpture, for instance, then, to me, it’s connected to the canvas because that was the author’s intent. (P2)

For a painting, I’m not expecting to see it in 3D. So if it’s already a flat image, I think I liked the [outline] or the bas-relief more ... If I’m used to seeing it as a 3D image, then I want to see the 3D model. (P1)

In fact, both participants who chose to assess naturalistic artwork preferred bas-relief representations of the artwork, and five of the six of participants chose to assess abstract artwork preferred either outline or bas-relief representations of the artwork.

#### **4.3.3.3 3D Models Preferred for Real-World Objects**

All participants also agreed that, in general, 3D model tactile representations were the best mediums for conveying objects that are truly three dimensional, especially in terms of communicating spatial relationships and in generating the most realistic final representations.

When asked about their criteria when assessing features of the resulting tactile graphics, a majority of participants responded that they looked for retention of key details and faithfulness to the original image.

#### **4.3.3.4 Use Cases for Multiple Representations**

Interestingly, all study users responded positively to the idea of presenting BLV individuals with multiple representations of the same image—whether 2D or 3D in its original form. Participants reasoned that this strategy would allow for more complete understanding, more individualized options, and increased concept building on behalf of the BLV end user.

P4 gave an example of, perhaps, beginning a classroom lesson with a 3D model to build more comprehensive spatial awareness of an image’s subject before moving on to an embossed graphic of the same image:

[In] a lot of textbooks and exams, students are provided with just, like, an embossed tactile graphic. So, say, they were having to learn how to label the parts of the heart, it would be good to start with the 3D model so that they can ... get a concept for ... the size ... [and] where all these different things are located, and then apply that knowledge from the 3D model to the 2D embossed diagram and learn where to correlate what’s there in real life to where it is on the diagram. (P4)

#### **4.3.4 RQ3. Automatically generated tactile graphics are broadly applicable across educational and cultural settings.**

Overall, participants found that our tool would be broadly applicable to their existing workflows in their respective fields for a variety of image types. However, two participants noted scenarios in which the tool may not be as useful.

P3 gave the example of looking at cells on microscope slides, saying:

[I wouldn't use the app] maybe if it was just too, too detailed. Like, something that we were trying to convey that even visually is too complicated ... Tactually, it's just indistinguishable. There's nothing that we're going to be able to do to make this accessible to them because it's barely accessible to our eyes. (P3)

Another example was given by P4 who remarked that she would likely choose to maintain her current workflow rather than using our tool specifically for math applications (graphs, charts, etc.) as bas-reliefs and 3D models are not necessary. That being said, our creation tool focuses on complex images rather than specifically data visualization.

##### **4.3.4.1 Speed and Cost-effectiveness**

All study participants also emphasized the speed and cost-effectiveness of our automated approach in comparison with hand-making and/or other tactile material design software.

I think this would be really useful in taking images straight from textbooks, so that students are having access to the exact same information as their peers ... textbooks and braille options and things are not as good, so we could just quickly make this without having a lot of, you know, sending it off or anything like that ... The fact that you can just upload an image and you can just convert it like that. That doesn't really exist ... not easily. (P3)

P6, an assistant curator at an art museum, explained that the "small team and limited resources" at her institution make it difficult to fully achieve accessibility goals, especially as a non-expert in tactile graphics creation. These constraints underscore the value of a quick, cost-effective solution like our automatic tactile graphics generation tool to improve accessibility for BLV patrons.

Additionally, participants commented positively on 3D printing as a cost-effective alternative medium for tactile graphics creation, noting the increasing availability of the technology at their respective institutions.

#### **4.3.4.2 Overcoming Lack of Availability**

Multiple participants reviewed our tool favorably regarding its capability to rapidly generate tactile representations for real-world objects that are either too fragile, large, remote, or unsafe to handle. One example of this, given by P4, included its potential application in "different health classes ... where [students] need a model because [they] can't necessarily feel the real thing" when it comes to anatomical diagrams.

This use case of overcoming lack of availability of real world objects was consistently put forward as rationale for embedding our tool in classroom and art gallery workflows.

#### **4.3.4.3 Applications for Sighted Users**

Tactile graphics in museum settings are viable learning tools not only for BLV patrons but also for sighted visitors. P1 emphasized that multi-modal experiences could create greater and enhanced engagement with museum exhibitions for all patrons, especially children.

We have a lot of digital exhibits ... [kids] see digital stuff everywhere ... They want to touch something. They want something that's not digital ... I almost feel like we're shifting toward a more tactile experience. (P1)

Thus, our tool’s application could potentially be extended to educational and cultural settings for the benefit of sighted and BLV persons, alike by enabling learning through physical interaction Foglia and Wilson (2013).

#### **4.3.4.4 Tactile Graphics as a Means of Breaking Down Barriers**

Several participants supported the mainstream application of automatically generated tactile graphics (i.e., utilizing them with a wider audience); thereby, countering the perception that these tools are only advantageous for people with visual impairments while, at the same time, increasing accessibility for BLV students and museum patrons.

All of the TSVI participants mentioned that tactile graphics in textbooks and on standardized testing are very difficult for students to interpret, our creation tool would be a useful tool for teachers to easily generate their own tactile graphics as a means of increasing their students’ tactile literacy. Two of the TSVI participants suggested that the outreach department at their campus would benefit from introducing non-expert teachers in local districts who may have BLV students in their classrooms to our creation tool to encourage them to provide greater accessibility for those students.

Both of the participants who work in museum spaces (P1 and P6) emphasized positive impact on the museum experience as a whole of not leaving out visitors with disabilities (BLV, cognitive disabilities, etc.). Both P1 and P6 commented on the importance of providing additional resources, as this benefits patrons of all abilities and fosters a more welcoming and inclusive environment for people with disabilities and their families.

Overall, participants agreed that having a tool to quickly, cost-efficiently, and easily create tactile graphics will lower the threshold of creating these supplementary tools and encourage non-experts to create more accessible learning environments.

## Chapter 5: Interpretation Pilot Study

After completing the authoring study sessions, we held informal pilot study sessions with two blind individuals to evaluate the printed tactile graphics that were generated with our tool.

The two pilot studies were each 60 minute, one-on-one, in-person sessions and were approved by our institution’s IRB. We compensated both participants \$20 for their time.

We recorded audio during each study and transcribed participant comments. We then conducted thematic analysis to group responses as they relate to our research questions.

| Interpretation Pilot Study Participant Information |     |        |                   |                  |                         |                                   |              |                                               |
|----------------------------------------------------|-----|--------|-------------------|------------------|-------------------------|-----------------------------------|--------------|-----------------------------------------------|
| ID                                                 | Age | Gender | Visual Impairment | Onset            | Occupation              | Experience Using Tactile Graphics | Frequency    | Preferred Mediums                             |
| 7                                                  | 43  | Female | Totally blind     | Acquired; age 2  | Tech Support Specialist | Some; Educational context         | Occasionally | Raised line                                   |
| 8                                                  | 36  | Female | Totally blind     | Acquired; age 10 | Teacher of BLV Students | Expert; Educational context       | Weekly       | Dependent on content; thermoform, 3D printing |

Table 5.1: Demographics of interpretation study participants.

### 5.1 Research Questions

- **RQ1:** What are BLV users’ preferences for each tactile medium in educational, cultural, or personal contexts?
- **RQ2:** How do BLV users perceive the usability and comprehensibility of automatically generated tactile graphics across different mediums (embossed outlines, bas-relief models, and 3D models)?
- **RQ3:** What do BLV users feel are the strengths and limitations of each tactile medium in conveying spatial and compositional information for a variety of

complex visual images?

## 5.2 Method

In these user study sessions, the two participants were asked basic demographic and background interview questions regarding their level of visual impairment, their personal experience using tactile graphics, and their existing preferences for various tactile graphics mediums 5.1.

Both participants explored 15 of the 21 available tactile graphics, which were previously generated using our creation tool using five randomly selected images. Each of the five images were available for the study users to manipulate in three different tactile mediums (embossing, bas-relief, and 3D). During each interaction, the participants also received image descriptions containing contextual information, as well as suggested touch strategies to help map tactile features to the original image.

After giving their unstructured feedback while assessing the tactile graphics, we then asked both participants about their impressions of each medium, including comfort of use, comprehensibility of content, and overall preferences between the three tactile graphic types covered in the study.

## 5.3 Results

### 5.3.1 Participant Background

Each of the two participants had prior experience using tactile graphics to interpret images. However, P7 had limited tactile graphics experience, having only used tactile graphics occasionally. P8 had more extensive tactile graphics experience, especially as it relates to her occupation as a teacher of BLV students.

**Participant 7:** The majority of P7’s previous experience using tactile graphics was in educational contexts. She explained that her tactile graphic encounters were most often thermoform raised-line drawings while exploring illustrations in books,

viewing tactile representations of artwork, and engaging with tactile coloring pages. When asked if she had a preference of tactile graphics materials, P7 explained that since most of her experience was with raised line drawings, it would have to be her “existing” preference by default.

**Participant 8:** Unlike P7, P8 makes regular use of tactile graphics in her classroom as a TSVI. Each week, her class will incorporate some type of tactile medium to enhance student learning outcomes. When surveyed about her preference for a particular type of tactile graphic, P8 said that she “like[s] thermoform as, like, paper,” but she also mentioned that she has recently begun experimenting with a 3D printer that her school recently acquired.

### **5.3.2 RQ1. BLV User Preferences.**

For all tactile graphics assessed in the study, P7 preferred 3D models, citing easier manipulation, comfort of use, and understanding A.1.

In contrast, P8 found several embossings and bas-relief models to be equally useful to some of the 3D representations A.2. She explained how she had some difficulty keeping track of the orientation of some of the 3D models, and the heightened level of detail would a little confusing without supplemental image descriptions. She did note, however, that in some cases a higher level of detail helped her to more fully understand the image content depending on the medium and image type.

### **5.3.3 RQ2. Usability and Comprehensibility of Automatically Generated Tactile Graphics.**

#### **5.3.3.1 Embossed Outlines**

P7 consistently rated embossing outlines as the least comfortable and least comprehensible tactile graphic medium for all five sample images A.1. Moreover, when compared to the thermoform raised line drawings she was more familiar with, P7 noted that the cardstock embossings created with the Cricut printer were not as

### Participant willingness to use each medium in the future.

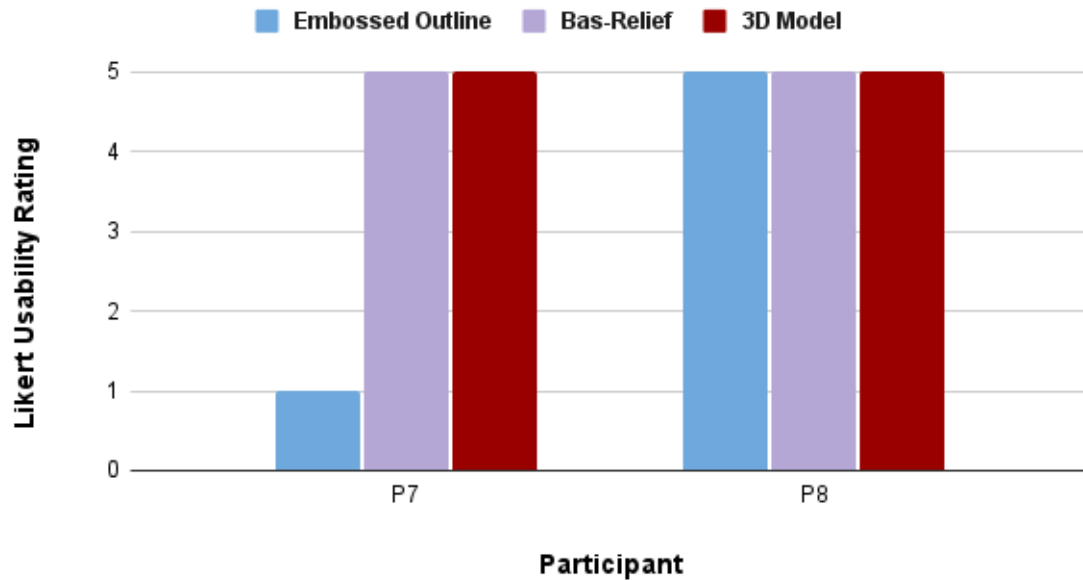


Figure 5.1: P7 and P8 both strongly agreed (5) that they would use bas-relief and 3D model tactile graphics in the future. However, while P7 strongly disagreed (1) P8 strongly agreed that she would use paper embossing tactile graphics in the future.

prominent. She also mentioned that the texture of the cardstock, itself, was not as smooth as thermoform paper, which contributed to her perceived difficulty in reading the embossed tactile graphics made with our tool.

It's just because the inset of these is harder ... I think [most of] the raised line drawings that ... I've seen in the past come off the paper a little bit ... it also matters the paper they're on because [raised line drawings are] on thermoform. (P7)

She qualified this preference, saying that even when embossings are more prominent (as with thermoform), raised line drawings are still difficult to fully understand.

Usually if [raised line drawings are] done a little differently, they're more prominent, but ... I've also seen those as well, and they're just difficult to interpret." (P7)

This raises the concern as to the usefulness of 2D tactile graphics for BLV people when attempting to view complex images, especially if bas-relief or 3D models are readily available, since, according to our study’s findings, these tactile mediums had higher ratings for both comprehension and utility.

On the other hand, P8 expressed a positive experience for embossing outlines with respect to both comfort and comprehension, depending on the specific image being studied A.2. For example, after manipulating an embossed outline of a frog, she remarked how she could “feel each leg pretty clearly,” and she especially liked that the outline did not have “too much detail.” She clarified her high rating, explaining, “Sometimes tactile graphics can get a little busy, but this one to me is very clear, and I can feel every aspect of it very well.”

### **5.3.3.2 Bas-Relief Models**

P7 liked the slight elevation of the images in bas-relief so that she could better understand an image’s shape, depth, and perspective. However, she also remarked that she was somewhat limited in getting a more comprehensive representation due to the bas-relief’s flat back. Overall, P7 still rated bas-reliefs relatively high in terms of comfortability and comprehensibility.

P8 also ranked the bas-relief models highly for comfort and for their ability to convey greater understanding overall A.2. She specifically cited the bas-relief model’s ease of use regarding depth perception. P8 expressed how she liked them “much better [than the outlines]” for exploring the contours, shapes, and relative positions of elements within the image, thus, conveying a sense of depth.

I do prefer to get depictions that are as close to reality as possible... Having it be as realistic as possible is nice... When it comes to paintings or portraits or anything, it’s really hard to get all that detail in [a paper graphic]. And if you do get all the detail in there, it’s confusing... I think the 3D or the bas-relief provide more feedback [than the traditional outline]. (P8)

### 5.3.3.3 3D Models

The participants' comprehension and usability were greatly enhanced with 3D models. These tangible representations of the study images allowed P7 to create more accurate mental pictures, which seemed to improve her overall understanding. She remarked that the 3D models were:

Pretty simple and [don't] ... leave you subject to ... 'oh, hey, what are these other things?' because some people get distracted by the smallest things ... It's simple—you know, the shape and everything ... I like it. (P7)

Similarly, P8 found most of the 3D models offered a level of detail that dramatically increased her comprehension A.2. And, although she had previously expressed concern over certain tactile mediums having “too much detail” that could potentially be confusing, especially among young BLV students, she gave all of the study's 3D representations high marks in all areas, including: comfort, comprehensibility, spatial relationships, and composition. For example, after manipulating a 3D model of the human heart, she said:

This one's cool ... I do like this one in 3D because you can feel where all of the attachments are for the veins and arteries and all that ... In this situation, more detail actually really, really helps.” (P8)

### 5.3.3.4 Image Descriptions

Image descriptions are intended to help blind or visually impaired individuals to better understand the overall content of an image, as well as the subject, composition, and context. Both participants were provided image descriptions for each of the five images used in their respective sessions while they manipulated the three different tactile graphics created for each image.

When P7 was asked if image descriptions were useful when feeling the various tactile graphics, she said they were, in fact, “very helpful.” She continued by clarifying

that “a lot of the time with art, it is helpful to have the description ... because art is unique, and people interpret it differently— even those who are sighted.”

P8 also emphasized the importance of including text descriptions while also using tactile graphics to aid the BLV end user in developing a deeper understanding:

Sometimes there is a disconnect between a concept of something and what it feels like or what it looks like. Particularly, if [someone] has been born blind ... there [are] ... gaps in understanding in some places. So, for that [reason], I think ... having the image descriptions in concert with the tactile [graphic] gives a fuller concept.” (P8)

Because image descriptions are often printed in braille to provide more information by supplementing with text, we asked both BLV participants how they would want braille to be incorporated with bas-relief or 3D models (if at all). P7 remarked:

On the bas-relief, I feel like there’s a place there ... to put braille because it’s on a flatter surface ... maybe not like a whole description, but you could just label it. Not on the 3D model though because ... it seems to be just what the object is and there may not always be space ... it might be distracting. (P7)

P8 agreed that adding text descriptions to a 3D model would be “helpful” but may, ultimately, prove “difficult,” saying that “if the braille was placed directly onto [the model], then it would hide part of the image.” She suggested having “a plaque ... next to where the 3D depiction is [located with] ... a description of [the model, which] ... would be separate from [the model, itself].” Applying braille to either embossings or onto the flat backgrounds of bas-reliefs seemed more straightforward and, therefore, more feasible.

### **5.3.4 RQ3. Strengths and Limitations of Spatial and Compositional Information.**

#### **5.3.4.1 Embossed Outlines**

P7 found embossed outlines difficult to interpret, especially the composition of an image and spatial relationships of objects within an image, due to a lack of prominent contour lines and an excess of fine detail A.1. Regarding one of the tactile graphics provided in our study, a naturalistic portrait of a woman with a neutral background, P7 noted, “If you hadn’t turned [the tactile graphic], I would not know that was the top of it. It all feels the same.”

Except for just one of the five images she assessed during the study, P8 agreed that the details in the majority of the embossings were too finely executed and “[did not] translate well into tactile [representations],” which made discerning key compositional features of the images challenging to interpret. When assessing an embossing of an abstract art piece, P8 remarked:

Oh no, I don’t like this one ... there’s too many lines ... [and] the lines, themselves, are not defined enough ... If you handed it to me upside down, for example, I wouldn’t be able to tell any difference in what ... this was versus [if you handed it to me] right-side up. (P8)

#### **5.3.4.2 Bas-Relief Models**

Overall, P7 found the bas-relief models to support a much higher degree of spatial awareness and compositional information about the study’s five images A.1. When interacting with a bas-relief representation of an artillery cannon, P7 explained:

I really like that you can feel the cannon and that you can kind of have an idea visually ... I don’t have 100 percent interpretation, but it’s close—it’s a good representation. (P7)

Interestingly, P8 gave the bas-relief models only moderate rankings for both spatial and composition information conveyance A.2. While she admitted that bas-

relief models were “better” than the outlines, she said she “still needed some description” to be able to interpret them since tactile mediums “with a lot of detail are still a bit more challenging” to ascertain.

#### 5.3.4.3 3D Models

Given that P7’s only prior tactile graphic experience was with thermoform raised-line drawings, she concluded that the 3D models were “more realistic ... [because] you can tell where everything is and the shapes are more realistic.”

Unlike 2D representations, 3D models can be rotated and manipulated to feel the object from different angles, providing a more complete understanding of its form and spatial details. When exploring the study’s images generated in 3D, P7 noted:

You have an exact portrayal of ... the shape and locations of ... different parts of [the object] because I think that’s something a lot of people don’t get when they’re feeling pictures on the paper.” (P7)

P8 also had a positive reaction to most of the 3D models, saying she “really loved [them]” because she was able to develop a much stronger mental image based on the heightened spatial information conveyed by the 3D medium.

However, she later clarified her high rankings of the 3D tactile graphics by cautioning that it was difficult to keep track of the exact orientation of some 3D models. Still, P8 agreed that “for the most part, when it comes to ... trying to understand a concept or what something looks like, if we can get [the tactile graphic] as close to how it actually looks [as is the case with 3D models], that’s better.”

## Chapter 6: Discussion

### 6.1 Overcoming Lack of Availability.

Across the two user studies, multiple participants highlighted the potential use case of 3D printed models for real world objects that are difficult to acquire or impossible to touch. For example, P1, a museum program coordinator, commented on the accessibility of museum artifacts, saying:

There’s so many things in the museum that kids can’t touch ... it would be really neat for them to get to feel something ... It’s nice for kids to get to touch things and be a part of things. (P1)

Several TSVIs presented examples of real-world objects that are inaccessible due to their real-world scale or location. When assessing generated graphics for an anatomical diagram of the human heart, P4 commented that her campus has “different health classes ... where you need a model because you can’t necessarily feel the real thing.” Similarly, P2 and P3 both gave examples relating to student field trips where surroundings, like architecture, monuments, and even trees, are difficult for students to grasp as they are not able to feel these large objects in their entirety.

”[Architecture] is always hard to convey, especially for students that have never had sight before ... [and] we do, like, experiential learning in nature ... There might be cases where we’d want to be able to produce a representation of something that they’re seeing in nature that they’re not able to touch ... Even just something like a tree comes to mind because they can only feel one part of a tree ... especially if it’s a tall tree.” (P2)

BLV participants corroborated this use case, reflecting on their own experiences in cultural and educational settings:

[Museum officials] really kind of frown on you touching [monuments] ... If blind kids go on field trips or something like that, they can't really get that close to [the monuments]. So maybe like miniature portrayals of those monumental figures or just other important things that they're learning about in school. (P7)

By enabling the rapid creation of tactile graphics for inaccessible real-world objects, our tool expands opportunities for BLV learners to engage more fully with their surroundings.

## 6.2 Context Dependence

Participants in the authoring study demonstrated the propensity to consider the context of each tactile graphic when choosing their preferred mediums for each image type, including learning goals for classroom lectures or museum exhibitions, the tactile comprehension level of the audience, and the dimensionality of the object being represented.

### 6.2.1 Concept Building vs. Direct Representation

Participants in both studies highlighted the importance of aligning tactile representations with specific educational goals—whether for building abstract concepts or directly representing physical forms.

In the authoring study, P4 reflected on how different mediums best communicate the “salient features” of an object. One example image that P4 assessed was a photograph of a fossilized dinosaur footprint embedded in a rock. For this image, the generated bas-relief provided a faithful reconstruction of the imprint while the 3D model appeared to resemble the foot of the dinosaur itself rather than the footprint. Rather than dismissing the 3D model as inaccurate to the original image, P4 considered how she might design a lesson around either of the two representations:

I was thinking about ... how best are the salient features of this object

or image communicated in each of the different models ... Like, with the dinosaur footprint, [I was] thinking about: do I want to teach, like, how a footprint is created and 3D print a foot ... or do I want [students] to feel the imprint itself? (P4)

Here, the choice of model supports either concept building (the process of footprint formation with the model of the foot) or direct representation (the fossil imprint itself).

In the interpretation study, P8 echoed this sentiment when assessing the same tactile graphics generated in P4's session, noting that some viewers, especially younger students, might be confused if only the foot model was presented when learning about an imprint fossil, but that providing both representations side-by-side could aid in concept building:

I think if you had both ... [In other words, the 3D model] ... is what the dinosaur's foot looked like, and then [the bas-relief] is the imprint that the scientists or archaeologists ... found that the foot fits into. (P8)

### **6.2.2 Growing Tactile Literacy**

Participants emphasized that tactile comprehension is not solely determined by the quality of the graphic itself, but also by the tactile literacy of the learner which is shaped by prior exposure to tactile graphics, age, and individual learning needs. As such, providing multiple representations of the same concept was widely regarded as essential for supporting a diverse set of learners.

P2 highlighted the importance of offering varied representations, noting that it would be especially important "for students who might have more difficulty understanding concepts" and that "presenting [the same image] in a couple ways to see which one resonates would be totally appropriate" and would be a strategy that she would employ in her own classroom with access to a creation tool that supported the generation of multiple representations.

TSVI participants in both studies also described how tactile graphic design often needs to be personalized based on a student’s level of tactile experience. P5 reinforced this point by sharing that even older students can have underdeveloped tactile skills if they haven’t had consistent exposure or access to a variety of tactile graphics:

Sometimes I’ll have a high school student where we just look at a very simple graph, and I still have to work with them to ... practice aligning the graphic and [perform] a systematic search of the graphic ... So it’s not necessarily graphics-specific, but more related to a student’s exposure to graphics. (P5)

These reflections suggest that developing tactile literacy is a gradual process. Multiple formats, such as outlines, bas-reliefs, and 3D models, can serve not only as alternate representations, but also as tools to support learners as they build fluency in interpreting tactile information. Our tool facilitates this learning process by enabling the quick and simultaneous generation of multiple representations from a single image, making it easier to tailor tactile materials to individual needs and learning goals.

### **6.2.3 Impact of Original Dimensionality**

Authoring study participants consistently preferred bas-relief and outline formats for representing two-dimensional artwork. These formats were viewed as more faithful to the source material, preserving the artist’s original intent and avoiding potential confusion about whether a painting or drawing was a sculptural object. By contrast, for objects that exist in three dimensions in the real world, participants overwhelmingly selected 3D models as the most effective representation. Users emphasized the superior ability of 3D models to convey spatial relationships that are difficult to capture in two-dimensional formats. As P4 explained:

I really liked the 3D models to convey three dimensional concepts ... because a diagram isn’t the same ... For most things that are real, three

dimensional objects that exist in the world, I really like that you have the option to create 3D models. (P4)

Interestingly, despite primarily having used raised line drawings, P7 showed a strong preference for 3D models across all image types (see Appendix, Table 3). Similarly, P8, a more experienced tactile graphics user, also favored 3D models overall, though less strongly than P7 (see Appendix, Table 4). These responses suggest that users with higher tactile literacy (like P8) may be more adept at interpreting a range of representations, yet still gravitate toward 3D models. This is likely because 3D models more closely resemble real-world objects and offer richer spatial information. Meanwhile, raised line drawings and paper embossings, being the most abstracted and least dimensional, may present greater comprehension challenges, especially for users with limited experience using tactile graphics. These preferences the importance of aligning the dimensionality of the tactile representation with both the user’s experience level in addition to considering the dimensionality of the object being represented. By allowing users to generate multiple representations of the same image ranging from 2D to 3D, our tool enables more tailored accessible learning experiences across a range of tactile literacy levels.

## **Chapter 7: Limitations & Future Work**

### **7.1 Greater Support for Blind Users**

#### **7.1.1 Evaluating Visual Results**

While the core functionality of our current prototype is screen reader accessible, we have yet to implement greater support for potential BLV users of the application. In the current implementation, previews of resulting tactile graphics are entirely visual which would require a BLV user to print out their results in order to assess their output. In a future iteration, we would implement a way for BLV users to gauge how well their results represent their input image (e.g., a scoring system or description of results) to aid in decision making when designing a tactile graphic.

#### **7.1.2 Image Descriptions**

After the completion of thematic analysis on responses from the authoring user study, we integrated automatic image descriptions using ChatGPT-4o to map from the output tactile graphics back to the original image. These descriptions are intended not only to give non-experts a starting point for supplemental descriptions to be read or displayed alongside tactile graphics, but also to increase accessibility for potential users with screen readers when evaluating their results. We hope to examine the usefulness of image descriptions in an authoring capacity in a future study.

### **7.2 Direct Manipulation**

Multiple participants expressed the desire to have finer control over adjustments to both the input images as well as the resulting tactile graphics. Suggestions included directly applying braille to output, adding other annotations or textures to output, blending or merging output files, and having tools to crop or center input images.

### **7.2.1 Braille**

TSVI participants of the authoring study noted that it would be useful to be able to add braille directly to the tactile graphics from within the creation tool. P2 commented that she may apply braille stickers to printed results, but that it would be convenient to have a tool to accomplish this internal to the creation tool. While this is not currently supported within our creation tool, a future iteration may include the ability to directly type and apply braille to output tactile graphics.

### **7.2.2 Annotations**

Two participants (P3 and P5) mentioned that their ideal tactile graphics creation software would include tools to add shapes, curves, or other annotations to their input. P3 suggested the addition of a tool to "draw on the image itself" to add details (e.g. circling an important feature of the image). Implementing this in a future iteration of our creation tool may provide greater support when generating labeled diagrams, especially in conjunction with braille text.

### **7.2.3 Texture**

In both the authoring sessions and the interpretation sessions, we asked participants about the importance of textural feedback when assessing a tactile graphic. Participants agreed that texture is an important component in being able to differentiate regions of a tactile graphic. Because of the necessary materials for printing (i.e., 3D printing plastic filament and cardstock paper), our current implementation is limited in terms of providing varied textural feedback to users.

Several TSVI participants proposed that their solution to a lack of realistic texture would be to use automatically generated tactile graphics simply to communicate size and shape of the represented object and would supply students with another material to feel in order to describe real world texture.

I think that, especially because 3D printing is becoming more and

more common, that [the students] are learning how to get information from that material, but ... it doesn't have the weight, it doesn't have the texture ... Maybe you could also then have—like if we were doing the frog—then have something that felt like frog skin as a supplemental material ... or if we were talking about a bird, we could feel feathers. (P3)

Another potential approach to mitigating the limited textural feedback of 3D printed tactile graphics may be applying additional materials after printing results. P5 highlighted the potential for this use case in tandem with recognizing the potential for automatically generated tactile graphics for representation of objects that may be difficult to acquire when assessing the 3D model result for an image of a fish:

Most of the time, you can't hold a fish in your hands. You can't get a sense of what a fish is like just by feeling a [paper] tactile graphic or even [by feeling] the bas-relief. You could even coat [the 3D model] in something slippery ... [It] would be fun to give kids the sense of what fish actually kind of feel like. (P5)

Traditional paper tactile graphics often include different texture patterns to delineate different sections of an image, but these textures may not be representative of features of the real world objects. In order to maintain a high level of realism, this kind of texture was not implemented in our current prototype. After assessing the printed tactile graphics, P7 remarked that adding textures to help differentiate between regions of tactile graphics in all three mediums might be helpful in being able to more successfully interpret their content. A potential future iteration of this project may explore image segmentation and texture mapping to achieve this effect on the different mediums. A future study may assess the impact that these textures might have on realism of results and success of interpretation.

### **7.3 Applications Beyond Accessibility**

Aside from applications in BLV accessibility, tactile graphics have the potential to be beneficial to children and students at varying levels of education as supplemental

materials. We hope to further explore this application in future continuation of this project.

## Chapter 8: Conclusion

We presented a tool to facilitate the creation of tactile graphics for complex images such as paintings, diagrams, and illustrations for non-experts. Through evaluations of both the creation tool and the printed tactile graphics and careful thematic analysis, we showed that automatically generated tactile graphics can provide teachers, museum professionals, and other non-experts with a quick, cost-effective way to contribute to increased accessibility to these complex images for BLV individuals. While there is room for improvement in the robustness of our application, our creation tool allowed users to quickly iterate on their tactile graphics designs to produce ready-to-print tactile graphics that suited the needs of their respective fields. BLV participants verified that 3D-printed models generated using monocular depth reconstruction and image-to-3D inferences are a viable and promising medium for communicating complex imagery in a way that is engaging, comfortable, and comprehensible.

## Appendix A: Interpretation Study Usability Ratings

| P7 Usability Ratings                       |                |              |                  |                  |        |
|--------------------------------------------|----------------|--------------|------------------|------------------|--------|
| Statements for each Tactile Graphic Medium | Image Category |              |                  |                  |        |
| Embossed Outlines                          | Animals        | Architecture | Naturalistic Art | Museum Artifacts | Nature |
| Comfort of use                             | 3              | 3            | 1                | 2                | 3      |
| Comprehensibility                          | 3              | 3            | 1                | 2                | 3      |
| Communication of spatial relationships     | 3              | 2            | 1                | 1                | 3      |
| Composition of image as a whole            | 2              | 2            | 1                | 1                | 2      |
| Bas-Relief Models                          | Animals        | Architecture | Naturalistic Art | Museum Artifacts | Nature |
| Comfort of use                             | 4              | 4            | 4                | 4                | 4      |
| Comprehensibility                          | 4              | 4            | 4                | 4                | 4      |
| Communication of spatial relationships     | 4              | 4            | 4                | 5                | 4      |
| Composition of image as a whole            | 4              | 4            | 3                | 5                | 4      |
| 3D Models                                  | Animals        | Architecture | Naturalistic Art | Museum Artifacts | Nature |
| Comfort of use                             | 5              | 5            | 5                | 5                | 5      |
| Comprehensibility                          | 5              | 5            | 5                | 5                | 5      |
| Communication of spatial relationships     | 5              | 5            | 5                | 5                | 5      |
| Composition of image as a whole            | 5              | 5            | 5                | 5                | 5      |

Table A.1: P7's Likert scale usability ratings for each tactile graphic medium and image category.

| P8 Usability Ratings                          |                                    |         |              |                     |              |
|-----------------------------------------------|------------------------------------|---------|--------------|---------------------|--------------|
| Statements for each<br>Tactile Graphic Medium | Ratings for each<br>Image Category |         |              |                     |              |
| Embossed Outlines                             | Anatomical<br>Diagrams             | Animals | Architecture | Museum<br>Artifacts | Abstract Art |
| Comfort of use                                | 3                                  | 5       | 3            | 3                   | 1            |
| Comprehensibility                             | 3                                  | 5       | 3            | 3                   | 1            |
| Communication of spatial relationships        | 3                                  | 5       | 3            | 3                   | 1            |
| Composition of image as a whole               | 3                                  | 4       | 3            | 3                   | 1            |
| Bas-Relief Models                             | Anatomical<br>Diagrams             | Animals | Architecture | Museum<br>Artifacts | Abstract Art |
| Comfort of use                                | 4                                  | 5       | 4            | 4                   | 3            |
| Comprehensibility                             | 4                                  | 5       | 4            | 4                   | 3            |
| Communication of spatial relationships        | 4                                  | 5       | 4            | 4                   | 3            |
| Composition of image as a whole               | 4                                  | 5       | 4            | 4                   | 3            |
| 3D Models                                     | Anatomical<br>Diagrams             | Animals | Architecture | Museum<br>Artifacts | Abstract Art |
| Comfort of use                                | 5                                  | 4       | 4            | 5                   | 5            |
| Comprehensibility                             | 5                                  | 4       | 4            | 5                   | 5            |
| Communication of spatial relationships        | 5                                  | 4       | 4            | 5                   | 5            |
| Composition of image as a whole               | 5                                  | 4       | 4            | 5                   | 5            |

Table A.2: P8's Likert scale usability ratings for each tactile graphic medium and image category.

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