The Tactile Graphics Helper: Providing Audio Clarification for Tactile Graphics Using Machine Vision

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ABSTRACT

Tactile graphics use raised lines, texture, and elevation to allow individuals with visual impairments access to graphical materials through touch. Tactile graphics are particularly important for students in science, technology, engineering, and mathematics (STEM) fields, where educational content is often sequestered in diagrams and charts. However, providing a student who has a visual impairment with a tactile graphic does not automatically provide the student access to the graphics's educational content. Instead, the student may struggle to decipher subtle differences between textures or line styles, and must deal with cramped and confusing placement of lines and braille. These format-related issues prevent students with visual impairments from accessing educational content in graphics independently, because they necessitate the student ask for sighted clarification. We propose a computer-based "tactile graphics helper" (TGH), which tracks a student's fingers as he/she explores a tactile graphic, and allows the student to ask for clarifying audio information about the tactile graphic without sighted assistance. Using an embedded mixed-methods case study approach with three STEM university students, we confirmed that format-related issues prevented these students with visual impairments from accessing some graphical content independently, and established that TGH can provide guidance in these situations.

Categories and Subject Descriptors

K.4.2 [**Social Issues**]: Assistive technologies for persons with disabilities

General Terms

Design, Human Factors

Keywords

Tactile graphics; image processing; assistive devices; finger tracking; mixed-methods; case study.

1. INTRODUCTION

Tactile graphics are adaptations of visual graphics in which lines have been raised and areas elevated or textured to make them accessible to touch. For students with visual impairments, tactile graphics provide critical access to educational materials, especially in science, technology, engineering, and mathematics (STEM), including the social sciences [13]. However, tactile graphics are relatively underused by students with visual impairments. For example, in a survey of academically achieving blind 9-19 year old students in the United States and Canada, only 45% reported encountering 3 or more tactile graphics per week, while 25% reported encountering 1-2 tactile graphics per week, 24% reported encountering tactile graphics only a few times per month, and 6% reported never using tactile graphics in school [31]. This is despite the inclusion of as much as 93.3% of graphics in braille transcriptions of secondary (9-12 grade) science and math textbooks [25], and feelings from the blind students that tactile graphics are helpful, particularly in math and science [31].

It is extremely important that students with visual impairments have access to the content contained in tactile graphics. Many STEM concepts, such as direction, quantity, and shape, are taught in ways that rely heavily on visual reference, which poses severe access issues for students with visual impairments unless presented in tactile form [11, 16]. The ability to use graphics provides a "critical moment" in a child's mathematics and science education, which accelerates further math and science learning [21]. This is because graphics support reasoning about abstract concepts that are difficult to grasp directly, such as slope and function [12, 11]. Therefore, lack of access to tactile graphics has been singled out as one of a handful of reasons, including low teacher expectations and lack of blind peers and role models, as a cause for low interest and pursuance of careers in STEM by blind students [4].

Given their importance, why aren't more students with visual impairments using more tactile graphics? One reason for the low use of tactile graphics is that there are often confusing elements, such as ambiguous symbols, that necessitate help from a sighted person, and prevent students from using tactile graphics independently. The lines, symbols, textures, and spacing on tactile graphics are not standardized, unlike the specific formatting rules associated with braille and the Nemeth braille code for mathematics [25, 30]. As a result, awkward placement of labels and the low discriminability of lines, textures, and relief (elevation) may prevent a student from accessing a tactile graphic's content [2, 31]. To deal with format-related issues in tactile graphics, students with visual impairments will often ask for clarification from a sighted teacher, paraprofessional, or peer [30, 31]. When a sighted assistant is not available, the student may be unable to use tactile graphics to complete his/her work.

In this paper, we first document the problems surrounding tactile graphic formatting as viewed by professionals who work with students who have visual impairments and university STEM students with visual impairments. Second, we propose a machine system that answers questions about a tactile graphic, such as "what is on this tactile graphic?" and "what is this I'm pointing to?" This system will enable students with visual impairments to work independently with tactile graphics.

2. RELATED WORK

Our system enables audio-tactile graphics, which link sound with touch to enhance a tactile graphic with audio. Early efforts in creating audio-tactile graphics focused on tactile maps, and allowed the user to press a location on the tactile map to trigger an audio label [14]. Examples of early audio-tactile maps include NOMAD [23] and Talking Tactile Maps [5], made in the late 80's and 90's. More recently, Touch Graphics, Inc. has developed the Tactile Talking Tablet (TTT), which is composed of a plastic frame that holds a tactile graphic against a high-resolution touch screen [20]. The touch screen is connected to a personal computer via USB, which runs software allowing the tactile graphic to become interactive. Touching the tactile graphic can trigger audio information, or ask the computer to perform more complex computations, e.g., calculate the distance between two selected locations. Attachment to a computer provides the TTT considerable power and flexibility, but limits its portability.

The CamIO system [24] extends the idea of audio-tactile graphics to audio-tactile objects. CamIO uses a mounted 3D camera and machine vision to watch users interacting with objects, and allows the user to trigger audio information about an object. Like the TTT, CamIO is run on a computer, limiting its portability.

A more portable solution for audio-tactile graphics is Touch Graphic's Talking Tactile Pen (TTP), which uses the Livescribe Pulse Pen [28] to provide audio information dependent on where the user touches the pen to a graphic. This is possible due to the pen's on-board microprocessor and camera, which points towards the tactile graphic. When the TTP pen is touched to a tactile graphic that is covered in a very fine, nearly invisible dot pattern, it can locate itself on the graphic and play audio to the user [19]. Its pen form-factor enables the TTP to be considerably more portable than the TTT, but still requires the specialized Livescribe Plus Pen hardware.

In contrast to the TTT, TTP, and CamIO, which require specialized hardware and/or connection to a computer, Tactile Graphics with a Voice (TGV) runs on a smart phone and can read information from QR codes placed on tactile graphics [3]. The main motivation for TGV is to remove braille labels from tactile graphics, which often clutter the tactile graphic and can be awkwardly placed to avoid intersecting with graphic elements. Replacing the braille labels with QR codes enables the user to access the label information on demand by pointing the cell phone at the QR code. However, this requires the user to aim a camera, which can be difficult for blind users [27, 18, 33, 32], and occupy a hand with holding the camera, which could otherwise be used for two-handed exploration of the tactile graphic.

3. TACTILE GRAPHICS HELPER (TGH)

The Tactile Graphics Helper (TGH) involves a mounted camera placed across the tactile graphic from the user, which views the tactile graphic and the user's hands (Fig. 1). Although our current prototype runs on a computer, like the TTT and CamIO, our eventual goal is to port TGH to a tablet. The tablet could be propped upright and use a mirror to point the camera towards the workspace, similar to [1].

Figure 1: Layout of student using TGH.

Using computer vision, TGH recognizes the tactile graphic and tracks the user's fingers to allow for a natural hands-free interface between the user and TGH. This keeps the user's hands free to explore the tactile graphic. The user can verbally ask TGH for information about the tactile graphic, such as details about what the user is pointing to.

3.1 Stored Tactile Graphics Information

TGH must know some things about a tactile graphic before is can be used. The information TGH needs includes (1) a matrix map that associates every pixel in the graphic with a label ID and (2) a YAML file describing the attributes associated with each label ID. These data are created through a short manual process (approximately 10 minutes per graphic) prior to TGH use. First, TGH takes a picture of the tactile graphic and automatically crops and rectifies the image by its typical method (described below). A human worker then loads this image into a custom annotation graphical user interface (GUI), which automatically creates an empty matrix map for the image, where each cell corresponds to an image pixel, and the corners of the matrix to the image's corners. The pixel size of the map, which can be changed by changing the resolution of the photograph, partially determines TGH's ability to resolve locations in the tactile graphic.

Using the annotation GUI, the human worker marks regions of the tactile graphic image with colors using a Microsoft Paint type interface, Fig. 2. Each color corresponds to a label ID that is placed in the corresponding pixels in the matrix map. The worker indicates for each label ID (color) the region's type (line, area, text, or point), characteristics (e.g., solid or dotted), function (e.g., tick mark or axis line), and quantity, which is stored in the YAML file, Fig. 3. Future implementations of TGH could generate a matrix map and YAML file as part of automatic tactile graphic creation (e.g., the systems proposed by [15, 22]).

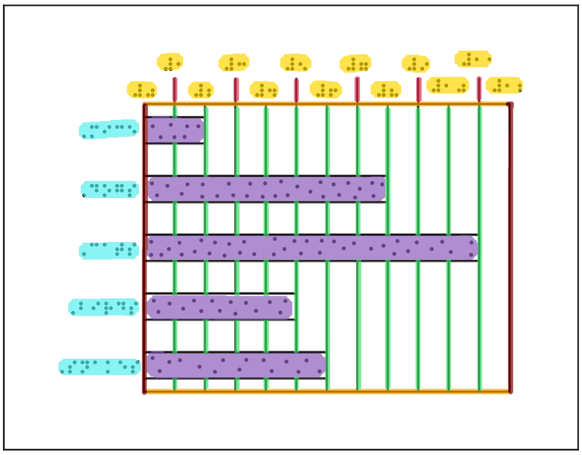


Figure 2: Tactile graphic shown in black, colors are worker-generated label IDs placed in the matrix map.

```
%YAML:1.0
Info:
    Matrix_Map_Filename: "TG_bars_matrix.txt"
    Reference_Image_Filename: "TG_bars_image.bmp"
    YAML_Filename: "TG_bars_description.yaml"
    Type: "Bar Graph"
    Title: "Animals in Pet Shop"
Features:
    F_1:
        Label ID: 1
        Title: "Data Bars"
        Type: "Area"
        Texture: "Dotted"
        Quantity: 5
   ...
```

Figure 3: Label IDs are described in YAML (excerpt).

3.2 Locating and Rectifying a Graphic

TGH requires a brief (approximately 3 second) initialization procedure to locate and rectify (remove projective and affine distortions) a tactile graphic before the user can begin exploring it with his/her hands. This procedure involves placing the tactile graphic within the camera's field of view, in what will be its permanent position. TGH locates the graphic by applying an edge detector [8] to the camera input, and detecting closed convex contours that have lengths within a specified range (the approximate size of the graphic). The longest contour with a four-vertex polygonal curve approximation (i.e., a rectangle) is recognized as the graphic's outer edge. TGH uses the four vertices, which constitute the graphic's corners, to create a rectified image of the tactile graphic, Fig. 4, which it associates with a stored matrix map of label IDs.

3.3 Fingertip Tracking

Finger tracking involves segmenting the user's hands from the background tactile graphic, and then identifying fingertips on the hands. The quality of the segmentation determines the reliability of the subsequent fingertip detection algorithm. Segmentation is accomplished with the background/foreground segmentation algorithm presented in [17], using 20 gray-scale training frames (collected right before the user begins exploring the tactile graphic) to build a distribution of the background's intensity values at each pixel. During tactile graphic exploration, pixels are classified as belonging to the user's hand if the intensity differs significantly from the background mean. Drops in segmentation performance can be caused by video compression and hard shadows, and necessitates using the estimated foreground mask as initialization for a secondary hue-based hand segmentation. In practice, this produces robust segmentation results in homogeneous lighting conditions (i.e., single color light sources).

Once a blob (foreground mask) of a hand is extracted, Fig. 5(b), TGH applies a distance transform to the binary image to extract ridges, Fig. 5(c). Ridges are then fit with lines using Ordinary Least Squares. Lines that are too short to be fingers are discarded, while the rest are marked as candidate fingers. Fingertips are located at one of the ends of each line, the end with a ridge value smaller than a pre-chosen threshold. The tracking algorithm also discards candidate fingertips that appear for less than 5 consecutive frames.

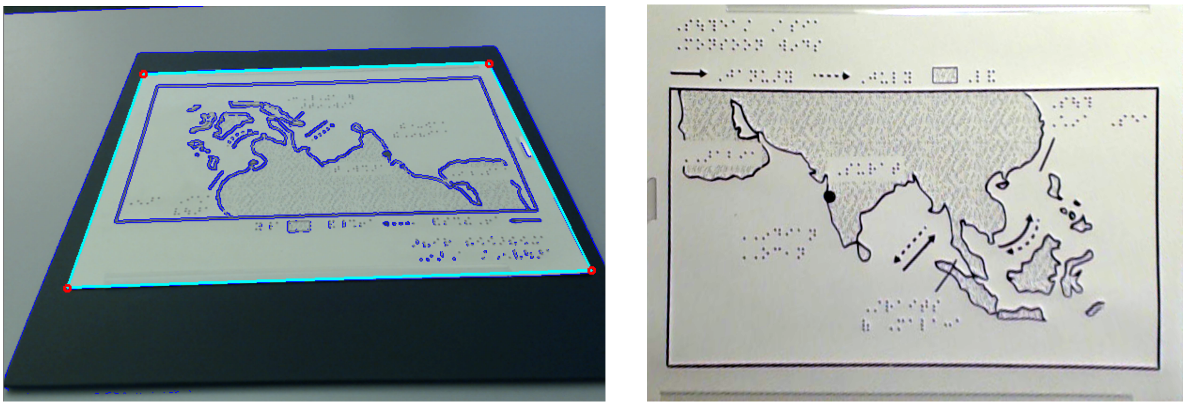
3.4 Voice Commands and Response

Users can interact with TGH using voice commands for hands-free audio information about a tactile graphics. TGH performs voice recognition and speech synthesis using Voce [26]. Currently, TGH responds to the commands "what is there?" which prompts TGH to list all of the titles of features and their quantities contained within the graphic's YAML file, and "what is this?" which prompts TGH to state the title of the feature the user is currently pointing at.

If the user asks "what's this" while pointing with one finger, TGH places the fingertip location within the stored matrix map to retrieve the closest label ID, and then retrieves the ID's title from the YAML file. If the user has multiple fingers extended, TGH cannot resolve what the user is pointing to and says "please use one finger." If TGH cannot detect any fingertips, it states "I can't see your finger."

4. FEEDBACK FROM TACTILE GRAPHICS PROFESSIONALS

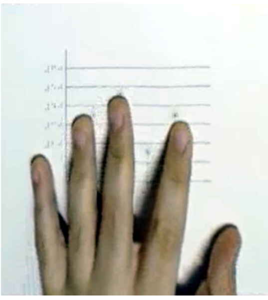
To guide our research approach, we solicited feedback from two professionals who are regarded as experts in visual-impairment accessibility, based on multiple years of experience working with students with visual impairments and en-



(a) TGH view, detected contour (cyan) and corners (red)

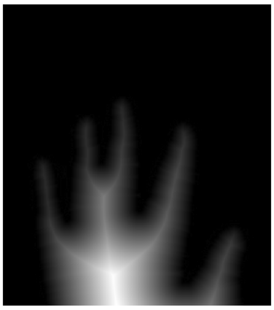
(b) Rectified graphic

Figure 4: Detection and rectification of a tactile graphic.

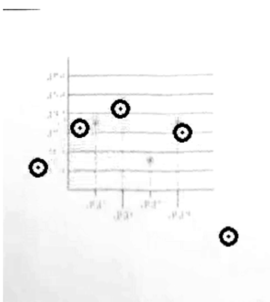


(a) Input image

(b) Segmented hand, blob



(c) Distance transformed blob



(d) Detected fingertips on input image

Figure 5: Example of fingertip detection.

gagement with professional networks by authoring newsletters and peer-reviewed publications. We described our system to these professionals, gave a demo of a working prototype to the second professional, and asked for feedback in an unstructured interview. Both professionals indicated that they had not worked with students who were using audio-tactile graphics.

The first professional, who worked mainly with primary and secondary school students, liked our general approach and confirmed that tactile graphics often contain formatting that prevent students from efficiently accessing educational content. He suggested that TGH should provide three distinct functions: (1) clarifying tactile graphic information (our original intention), (2) previewing tactile graphics (prompting us to add the "what is there" command), and (3) promotion of effective tactile exploration strategies. He explained that students can not just "go" when given a tactile graphic, they need to be oriented to the graphic through previewing, which involves orienting the student towards graphic elements, such as the location of axes and labels, and ensuring that the student can grasp these elements' content and function. Previewing is generally executed by an educational assistant or a braillist who works with the student hourly. Ultimately, students should learn to preview graphics on their own, but TGH could preview graphics for younger students, and could help older students complete school work with graphics more efficiently.

The second professional worked mainly with university students, and indicated that the ability to easily author audio information, by professionals and non-experts, was extremely important. The difficulty of authoring content prevented her and her colleagues from adopting technologies like the TTP. She felt that the time required to annotate tactile graphics (approximately 10 minutes) would not be problematic, because this was relatively short compared to how long it took to design a tactile graphic (one to several hours). Regarding the type of information provided by TGH, she suggested that personalization depending on student needs or context was very important, for example, more information could be provided for homework graphics and less on exam graphics. She felt it was unlikely that students would use TGH in a classroom, given their limited desk space. She also suggested that the system should have the option to subvert audio input, using instead either a gesture or keyboard interface.

5. MIXED-METHODS CASE STUDIES

5.1 Methods

To investigate whether format issues prevent access to content in tactile graphics for university STEM students, and whether TGH could be helpful in these situations, we used an embedded mixed-methods case study design [10, ch. 3]. Mixed-methods allowed us to triangulate (corroborate) evidence of format issues and possible uses of TGH, using both qualitative and quantitative data [7]. Our approach involved a fixed design, where the procedures of the study were planned in advance [10]. Each participant completed in order: (1) an initial semi-structured interview about the participant's general demographic information, his/her visual impairment, and experiences with tactile graphics; (2) an experiment in which the participant explored and answered questions about tactile graphics; and (3) a final semi-structured interview to gather the participant's impressions about TGH and its intended purpose. All procedures were video recorded and later transcribed.

Three participants were chosen because they were university students with STEM majors who use tactile graphics. All participants had directional light perception and could detect some form (e.g., the location of a window during the day in a dark room). The participants had no disabilities other than visual impairments. Similarities between the participants were desired to provide literal replication of results [29]. XXXX approved the study's procedures, and participants provided informed consent to participate in this research.

The purpose of the intruding experiment within the context of a qualitative multi-case study was to examine whether participants' reports about format issues could be observed in practice and to document their performance with TGH. This also allowed participants to ground their final interviews in recent tactile-graphics experiences. The experiment involved one practice (scatter plot) tactile graphic using TGH, and six testing tactile graphics. All tactile graphics were adapted from available educational and assessment materials, and produced on 8.5 x 11 in. swell paper. The six testing items consisted of two geometry graphics: (1) two side-by-side sand timers depicting types of symmetry, (2) two side-by-side circles depicting chords; two data plots: (3) a bar chart, (4) a line graph; and two maps: (5) drought in Africa, and (6) monsoon winds in Southeast Asia. (Items 1, 3, and 5 are shown in Fig. 6, and item 6 can be seen in Fig. 4.) Participants used TGH on half of the graphics, one randomly selected from each type. Geometry graphics were always first, data graphics second, and maps third, but otherwise the order was random. The participants were allowed to explore each graphic for as long as they wished before being asked 2-3 format-related questions (e.g., "what do the solid arrows represent?") and 2-3 content-related questions (e.g., "how many more snakes are there than mice?").

5.1.1 Analysis

Theoretical thematic analysis [6] was used to identify themes in the transcriptions related to tactile graphics and TGH. Both authors examined the data and agreed on a codebook that included the themes:

1. Opinions about tactile graphics, positive or negative.
2. Opinions about TGH, positive, negative, or wanting additional functionality.
3. Errors or uncertainties with tactile graphic format, content, or exploration strategies.
4. Using TGH to get or confirm information.
5. Mishearing TGH information or forgetting commands.

The last three themes (3-5) were behaviors that could occur during the experiment, and not during interviews. Themes 1-2 could appear throughout the entire procedure.

Using the codebook with rules for coding, the authors coded 30% of the data. Excellent levels of reliability [9] were obtained (κ = 0.90, % agreement = 91%), and the second author completed coding the remaining data.

5.2 Participant Descriptions

P1 was a college Junior (20 years old) studying Earth Science and Statistics. His visual impairment was due to Retinitis Pigmentosa (RP), which caused gradual vision loss starting at five years old. Although he had a vision teacher since the age of five, P1 began learning braille at 15, and had taught himself contracted (grade 2) braille and Nemeth using information from the Internet. He also reported no specific lessons with tactile graphics. As part of his school work, P1 used approximately 50 tactile graphics per week. He only used graphics outside of class, because they were "not ready in time" to be used during lecture.

P2 was a college senior (23 years old) studying Psychology. Onset of vision loss was at birth due to Leber's Congenital Amaurosis (LCA). She had briefly used magnified print graphics in high school when studying AP calculus, because "they didn't have enough resources to make [tactile graphics] in a timely fashion." However, in all other circumstances she had used tactile graphics. Despite having a vision teacher since the age of five, and having explicit lessons in Nemeth, P2 reported no specific instruction with tactile graphics. As part of her school work, P2 used approximately 20 tactile graphics per week. She rarely used tactile graphics in class because "by the time you find the tactile graphic, they're already on the fifth one." She also did not use tactile graphics for non-school purposes.

P3 was a college junior (21 years old) studying Linguistics. Onset of vision loss was at birth due to LCA. She had a vision teacher since she was three years old. However, by the time P3 reached high school, her vision teacher only provided braille materials and did not have specific time set aside for instruction. P3 indicated that she started learning braille at three years old, Nemeth at five years old, and tactile graphics at four years old. P3 was the only participant who reported receiving specific instruction with tactile graphics, beginning with simple shapes when she was four years old. However, P3 infrequently used tactile graphics. She reported that there were isolated classes that necessitated using about one tactile graphic per week in class, to study syntactic trees and the Persian alphabet. She did not use graphics more than about once per month for schoolwork outside of class. However, unlike the other participants, she reported using tactile graphics for personal use, roughly twice a month she would "look in [her] atlas."

5.3 Qualitative Results

5.3.1 Opinions About Tactile Graphics

Participants indicated that they all liked tactile graphics, and found them useful for their STEM courses. However, they complained that tactile graphics are slow to read and produce, and not readily available. Furthermore, all three

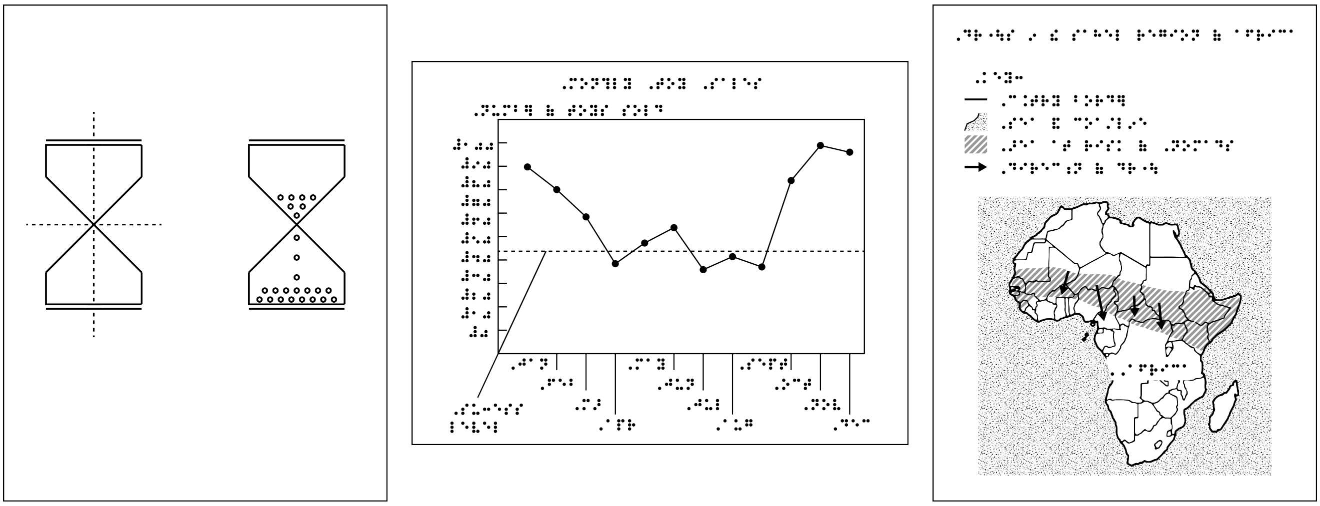


Figure 6: Three of the six test tactile graphics in the user study.

participants indicated that they had experienced format-related difficulties with tactile graphics. For example, P1 recalled a situation with an arrow placed on top of a longer dotted line, making the two difficult to tell apart. P2 reported that it was difficult to differentiate brain structures in her anatomy diagrams, and P3 similarly felt that there was often too much detail put on graphics, which "mushed together" and made the graphics difficult to understand. In general, all three participants indicated that they had experienced ongoing and past issues with lines and textures that were difficult to tell apart, elements placed too close together, and text in confusing locations. When asked how they typically overcome these format issues, all of the participants indicated that they ask for sighted assistance.

P2 and P3 were particularly concerned with 3D geometric figures in tactile graphics, such as line drawings of cylinders and pyramids. This issue was brought up repeatedly, especially by P3, who recalled that she had failed a test in elementary school due to these types of graphics. She suggested that this issue could be helped by TGH indicating surfaces as front, back, left, etc., and similarly with edges.

5.3.2 Opinions About TGH

All three participants thought that TGH could help with tactile-graphic format problems, including clarifying 3D figures. Participants imagined that they would use the system mostly for homework, and not in class. However P1 suggested that if the system could respond to gesture commands, he might use TGH in class to ask questions about tactile graphics without disturbing his classmates.

All of the participants disliked TGH's reliance on audio/voice input and output. The voice input created reliability problems in noisy settings. Participants wanted to have control over the voice output speed, and the ability to pause output to process information. Neither of these functions were possible with the current prototype.

The participants disagreed about what type of information they wanted TGH to provide. Both P2 and P3 liked that TGH would tell them the function of braille (e.g., "title") without reading the braille. In contrast, P1 insisted, "if I point to a word, I want it to read it out. Sometimes I'm lazy." There was a similar disagreement over textures, with P3 wanting textures to be indicated as "rough" and "smooth," and P2 preferring "water" and "land." However, P3 later suggested that TGH could provide information not printed on tactile graphics, such as the name of unlabeled countries. Not only did the participants disagree about what type of information should be provided by TGH, but participants' opinions were not consistent.

5.3.3 Tactile Graphics Errors

A consistent error across participants occurred when we asked them to point to the city of Surat and the location of the South China Sea on the map of Southeast Asia. In all instances, except when P1 corrected himself in pointing to Surat, the participants pointed to the braille label and not to locations marked with the relevant point symbol (dot) or label line. The participants also had difficulty in locating months associated with data points in the line graph (Fig. 6), because it was difficult for participants to move in a straight line between the data points and x-tickmark labels. Finally, all participants had difficulties differentiating the lined and stippled textures on the Africa map, difficulties locating the arrows within the lined texture on the Africa map, and struggled to understand the function of the label line on the line graph. For example, when asked for the meaning of the solid line in the lower left on the line graph (a label line), P2 responded that "it looks like a slope of some sort. I don't know what it is for."

5.3.4 Using TGH

Participants used TGH to both confirm and get information about the tactile graphics. For example, P2 indicated that she suspected the band across Africa was the lined texture, but couldn't easily differentiate this from the stippled texture, so she confirmed this using TGH. P1 also successfully used TGH to figure out that the solid line in the lower left of the line graph was a label line, used to label the dashed horizontal line as "success level."

The participants relied on TGH to "preview" the tactile graphic before exploring, by asking "what is there?" P1 was explicit about this, explaining to the researchers on the first graphic that he would always ask TGH for this information right away, and then systematically explore the graphic by examining the axes, then axes labels, etc. The information learned about the graphic from previewing was often repeated verbatim as answers to questions, without the participant checking the graphic to confirm the information was correct. For example, when asked how many bars there were on the bar chart, P2 said "the machine told me five. I was too lazy to count."

P3 was unique in that she asked TGH a large number of questions to see how it would respond to ambiguous situations, such as a point of intersection for multiple axes and lines, and the space between gridlines (in non-annotated empty space TGH says "nothing"). She typically embarked on this exercise after using TGH to gather more typical information about the graphic. Only P2 had issues forgetting TGH commands or mishearing TGH responses, and these occurred only once each.

5.4 Quantitative Results

The amount of time participants explored graphics before saying they were ready for questions is shown in Table 1.

Table 1: Exploration time (sec).

	TGH	Geometry		Graphs		Maps	
P1	with	Circles:	162	Line:	176	Asia:	268
	w/o	Timers:	34	Bar:	100	Africa:	268
P2	with	Timers:	75	Bar:	118	Africa:	122
	w/o	Circles:	20	Line:	37	Asia:	60
P3	with	Timers:	237	Bar:	318	Asia:	914
	w/o	Circles:	36	Line:	159	Africa:	184

Exploration times (in seconds) were modeled with a linear mixed effects model, with a random effect of participant (SD = 134.71, 95% CI: 94.18, 192.66) and fixed effects of type (geometry, data, or map) and TGH (with or without). The model revealed a significant main effect of type $F(2, 15) = 3.84$, $p = 0.045$, and a significant effect of TGH $F(1, 15) = 6.82$, $p = 0.020$, $est = -82.89$ ($SE = 31.75$). Overall, participants spent more time exploring graphics when using TGH than without.

The time spent exploring graphics was likely related to the number of questions participants asked TGH, Table 2.

Table 2: Number of times participants asked TGH "what is there?" and "what is this?" separated by commas.

	Geometry		Graphs		Maps	
P1	Circles:	1, 1	Line:	1, 1	Asia:	1, 2
P2	Timers:	1, 2	Bar:	1, 3	Africa:	1, 5
P3	Timers:	1, 14	Bar:	1, 12	Asia:	1, 19

6. DISCUSSION

This research confirms that tactile-graphic format issues pose accessibility hurdles for university STEM students with visual impairments. Format issues include lines and textures that are difficult to tell apart, tactile elements that are placed too close together, and text in confusing locations. Furthermore, we confirmed that TGH can help students overcome these issues.

Previous research documenting student difficulties with tactile-graphic formatting addressed tactile graphics broadly, not focusing on STEM, and included only students in primary and secondary education, not post-secondary [2, 31]. Our finding that university STEM students continue to struggle with tactile-graphic formatting highlights the severity of this issue - if these students have problems, students who are younger and have less experience in STEM are likely to be struggling even more. Future work is needed to establish whether TGH can support younger and less advanced students. However, based on feedback from the current participants that they would have liked such a system when they were younger (e.g., for 3D figures), we are optimistic that TGH can benefit students with visual impairments from a range of educational levels.

Participants explored tactile graphics for longer when using TGH than without TGH. This may have been due to more thorough examination of the tactile graphics when using TGH. When not using TGH, participants may have waited to explore a tactile graphic until they were asked questions about the graphic. Alternatively, participants' exploration times may have been extended by their interest in testing TGH's capabilities (e.g., the number of times P3 asked "what's this?" shown in Table 2). What is clear is that all participants indicated that TGH was helpful, and there were examples of each participant relying on TGH for information or clarification.

Based on feedback from one professional on previewing tactile graphics, TGH listed tactile graphic features when asked "what is there?". This implementation of previewing is not as comprehensive as what a teacher would do with a student, but participants found it very useful. By extending the finger tracking capabilities, TGH could provide a previewing experience more similar to what a teacher provides, e.g., asking the student to locate features on the graphic. TGH could also be used to encourage students to use effective tactile exploration skills, such as exploring the graphic systematically and using both hands.

There are several ways TGH could be improved, based on participants' opinions and errors. To be more useful, TGH needed to inform students when labels are associated with point symbols or label lines, because all students wrongly pointed to braille labels when asked to point to locations. The system should also support gesture input and allow greater control over the audio output. Finally, different modes of operation or personalization would allow teachers and students to decide the level of detail and type of information TGH provides, which may depend on the abilities of the student (e.g., low or high tactile acuity), the educational goal of the graphic, and context (e.g., homework versus test).

In conclusion, our findings highlight the format-related problems students encounter with tactile graphics, including line styles or textures that feel too similar to tell apart, features that are too dense to individually discriminate, and awkward placement of braille labels. These problems are commonplace in STEM graphics and cause persistent access issues for even advanced university students who rely on numerous graphics (20-50 per week) for educational content. Replacing sighted assistance with a machine-based system to clarify tactile-graphic format issues was largely successful, although there is room for improvement. With further refinement, TGH should be able to improve students' skills and efficiency in accessing educational content contained in tactile graphics.

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