Constructive Visualization to Inform the Design and Exploration of Tactile Data Representations

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ABSTRACT

As data visualization has become increasingly important in our society, many challenges prevent people who are blind and visually impaired (BVI) from fully engaging with data and data graphics. For example, tactile data representations are commonly used by BVI people to explore spatial graphics, but it is difficult for BVI people to construct and understand tactile representations without prior training or expert assistance. In this work, we adopt a constructive visualization framework of using simple and versatile tokens to engage non-experts in the construction of tactile data representations. We present preliminary results of how participants chose to interpret and create tactile data representations and the preferred haptic exploratory procedures used for retrieving information. All participants used similar construction strategies and converged upon 3D compact spatial forms to retrieve and display analytical information. These insights can inform future data visualization authoring and consumption tools that users of more diverse skill backgrounds can effectively navigate.

CCS CONCEPTS

• **Human-centered computing** → Accessibility; Accessibility design and evaluation methods.

KEYWORDS

Haptics, Tactile Graphics, Constructive Visualization, Data Visualization

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1 INTRODUCTION

Data visualization has become increasingly important in our society, augmenting the way we learn, work, manage personal finances, interpret current events, amongst numerous other facets of our daily lives. However, many challenges prevent blind and visually impaired (BVI) people from fully engaging with data and data graphics. One challenge is that BVI people often need to rely on specialists to create alternative forms of spatial graphics [5]. Studies have documented several benefits of the act of constructing data visualizations, which include deeper understandings of datasets, critical engagement with the visualization process, and reflections of the data in the context of personal actions and values [1, 11, 15].

Another challenge is that exploration of these spatial graphics can be difficult for BVI people who have not been trained. Tactile graphics, for example, are commonly used to convey spatial information [5, 13, 17], but the ability to understand them depends on the user's familiarity with effective exploratory procedures and strategies [11, 16]. To make data graphics more approachable, significant research efforts investigate ways to augment the exploratory process [6, 10] as well as alternative forms of representing spatial information that leverage different spatial cues and types of interactivity [8, 12, 14].

The emergent paradigm of constructive visualization, or the creation of flexible and dynamic visualizations using simple, familiar, and versatile elements, presents a framework for engaging non-experts in the process of manipulating and constructing data visualizations [7]. We apply this framework to observe how BVI people construct and interact with a tactile physicalization of a sample dataset using stackable magnetic tokens. Versatile manipulatives such as magnetic tokens, Wikki Stix, and stackables, are commonly used to teach BVI students spatial graphics in educational settings [4, 11]. We see constructive visualization as a promising way to gain insight into tactile representations and corresponding exploratory procedures that are more broadly accessible to the BVI community, all-the-while engaging non-experts in the construction of tactile data representations. These insights can inform future data visualization tools that users of more diverse skill backgrounds can effectively navigate.

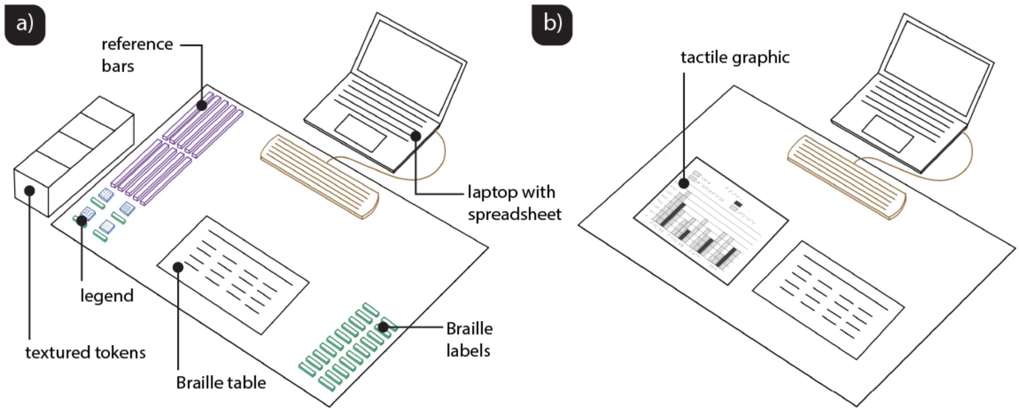

Figure 1: Interaction environment for a) task 1, which involved users constructing data representations using textured tokens, reference bars, and braille labels and b) task 2, which involved users consuming a standard tactile graphic. Design of tokens and tactile graphics were based on BANA guidelines [3].

2 STUDY DESIGN

In this work, we adopt a mixed methods approach that uses a combination of direct observations, surveys, and interviews to observe how BVI people: 1) organize data into graphical constructions, 2) use their constructions to retrieve analytical information, and 3) reconfigure their constructions to retrieve analytical information. We compare constructive visualization with a baseline of consuming pre-made tactile graphics. The videos and qualitative comments are codified using a grounded theory approach. We derived our coding scheme from relevant haptic exploratory procedures identified in Klatzky and Lederman [9] in addition to whether participants simultaneously explored the graphic with one or two hands. We chose to initially code participants answering questions related to minimum and trend identification because they require participants to navigate through specific groups of values.

2.1 Participants

We recruited 3 participants through local community organizations. All participants self-identified as blind and were between 55-65 years old. P1 is an assistive technology specialist who frequently read tactile graphics, while P2 and P3 did not have extensive tactile graphics experience. Participants spent roughly 90 minutes and received 50 USD.

2.2 Procedures

After filling out a consent form and demographics questionnaire, participants completed three tasks using sample datasets that showed a fictional bank account spending statement. For each task, we asked participants to think aloud. In task 1 (construction), participants constructed a graphical representation of the sample dataset and answered a set of analytical questions relating to the dataset based on their construction. In task 2 (consumption), participants were given time to familiarize themselves with a premade tactile graphic that represented a similar dataset before answering a similar set of analytical questions. In task 3 (transformation), participants were encouraged to reconfigure their constructions from task 1 in order to answer the last set of analytical questions and were aided in "resetting" their constructions to previous forms at any time upon request. Participants answered a series of post-study questions following the third task.

2.3 Setup

Dataset: Participants accessed the dataset through a Braille embossed table on an A4 sheet and on a spreadsheet vocalized through a laptop and screen reader. We used similar datasets for task 1 (construction) and task 2 (consumption) that showed four months of spending grouped into four spending categories. We based these datasets on ones used by Huron et al. [7] because they are broadly relatable and can be represented in many ways. Task 1 materials are shown in Figure 1a and task 2 materials are shown in Figure 1b.

Analysis Questions: We asked participants similar sets of analytical questions to observe how they retrieved information from their constructions (task 1) and from the tactile graphic (task 2). In task 3, we encouraged users to manipulate constructions to answer 5 additional analysis questions. Analysis questions were based on Boy et al.'s visualization literacy assessments [2] (included in the supplementary material).

3 RESULTS AND DISCUSSION

We present initial results for three participants prior to suspending user studies in light of the Covid-19 pandemic. As expected, participants took more time constructing their datasets in task 1 (15-20 minutes) than familiarizing with the tactile graphic in task 2 (2-14 minutes). The total time participants took to answer analysis questions varied less and was on average shorter when participants referenced their constructions (10-12 minutes) compared to the tactile graphic (9-22 minutes), which we hypothesize is a result of the varying levels of familiarity participants had with tactile graphics versus their own constructions. We summarize common representation themes and strategies below.

Similar construction processes with different forms: In task 1, all three participants approached their constructions by first forming the structural elements of graphical representations

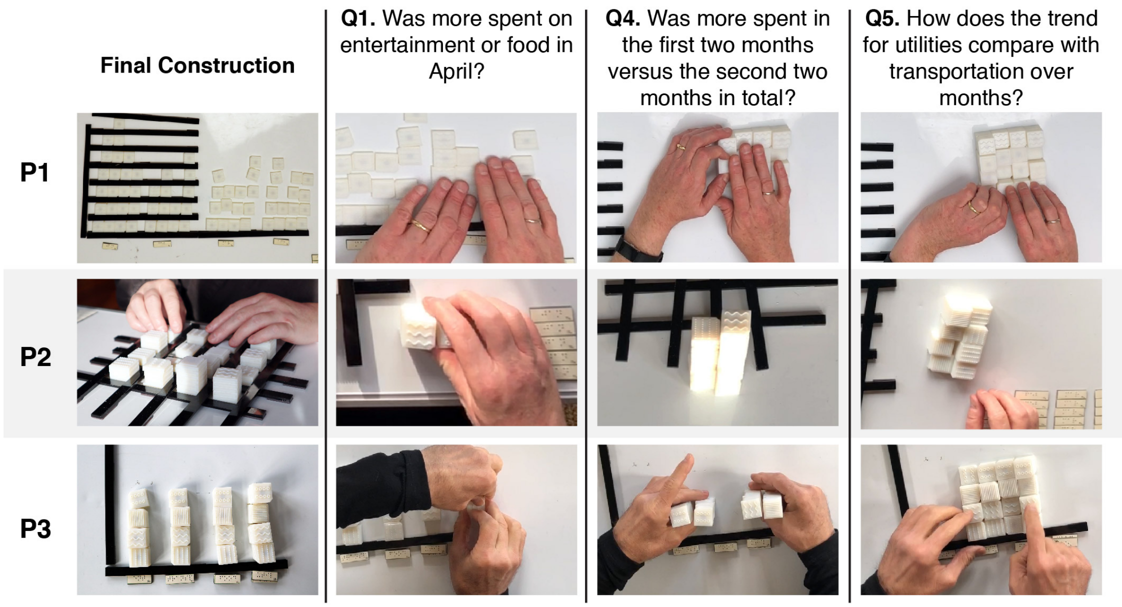

Figure 2: Participants reconfigured their constructions to answer analytical questions. All participants converged on a compact 3D form that facilitated side-by-side comparisons of height.

using the reference bars, then assigning labels if labels were used, last filling the graphical structure with data represented as tokens. Reference bars served two main functions when placed first on the canvas: 1) they organized the loading of data and 2) they formed a way for blind people to navigate their constructions. P2 describes the latter purpose: *"...borders are the most important thing there is for navigating anything– I can't deal with empty space, so the more borders there are, the more so-to-speak context there is for something, the better I can navigate whatever it is."* While the construction process was the same, the final construction form and use of materials differed between the three participants (Figure 2, left-most column). P1, who is a frequent tactile graphics reader, constructed a 2D vertical bar-chart representation of the dataset that most-closely resembled the embossed tactile graphic. P2 and P3 stacked tokens into a 3D representation of the data with month on one axis, category on a second axis, and spending on a third vertical axis.

Different retrieval strategies for construction than consumption: Participants used different combinations of exploratory procedures when retrieving analytical information from their construction compared to the tactile graphic as shown in Figure 3. One potential contribution to these differences could be traced to inherent differences in the representation elements. Participants used contour following more frequently with the tactile graphic, typically sweeping across horizontal gridlines to compare spending amounts or determine spending values, even for constructions in which reference bars resembled gridlines. The larger spatial footprint of the tokens could have reduced the spatial precision needed to accurately navigate the graphic. With the constructions, participants more often leveraged enclosure, enabled by the more

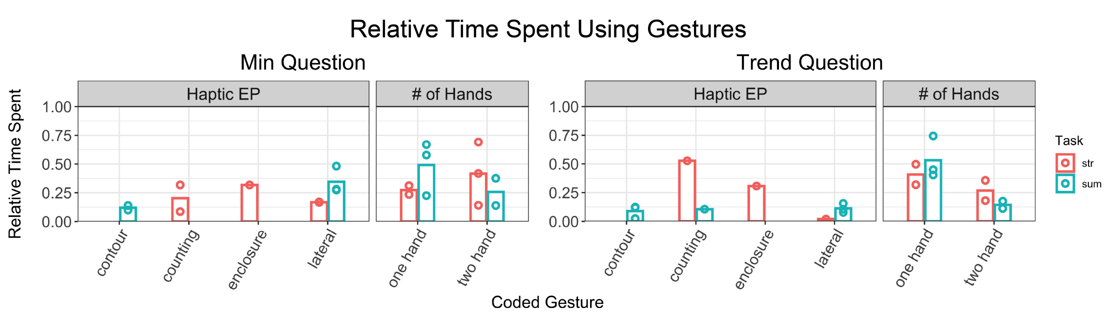

Figure 3: Plot comparing the relative time spent using gestures on task 1 (construction) and task 2 (consumption) for questions relating to minimum and trend identification. We define relative time as the amount of time spent engaging in coded gesture normalized by the amount of time taken to answer the corresponding question.

the prominent geometric features of the construction elements, and counting, due to the lack of numeric identifiers. Another contribution to observed exploratory procedure differences may be an outcome of how data is internalized during the construction. For example, P3 did not need to reference the construction but did reference the tactile graphic to answer the trend description question.

3D form facilitates "gestalt" overview and comparisons: When asked to manipulate their constructions from task 1 to a representation that was best suited to retrieve different categories of analytical information (e.g. min/max, trends), all participants converged to the same spatially condensed, 3D form. Figure 2 shows the forms each participant used to answer the different questions. For questions that involved comparisons such as Q1 (compare spending) and Q4 (compare trends), participants opted to manipulate the form in a way that would facilitate *height comparisons*. First, participants would move the relevant values next to each other with no space in between. All participants made similar comments as P1, who said: *"it's very easy to compare the trends in the various categories side by side when you compare the 3D dimensions between two categories. It's much easier to tell very quickly what the trend is where."* Next, participants compared heights using two hands, each following a different value, *"and you can just feel as you progress through the months"* as described by P3. Participants also commented on how the 3D form allowed them to get a better overview compared to a 2D form, "*[With 2D form] I couldn't actually look at all the data at once the way I can in this 3-dimensional representation.*" (P1), and *"[3D construction is] much easier to compare stacks across, can tell height easily even without rearrangement"* (P3).

4 CONCLUSION

Although significant research and academic effort aims to improve access to graphical information, constructing and understanding tactile representations without prior training or expert assistance remains a challenge for BVI people. We present preliminary results for how three BVI people create and retrieve information from visual representations using tactile tokens. All participants used similar construction strategies and converged upon 3D compact spatial forms to retrieve and display analytical information. While participants were able to construct any representation of the dataset, the provided authoring tools limit and may bias the representation form to variations of bar graphs. Observations and comparisons in this study may also not generalize to other types of graphical representations, which is a potential direction for future studies to explore. Continued work will analyze whether certain exploratory procedures correlate with retrieval performance when addressing the different types of analytical questions and explore differences between expert and novice tactile graphics users. These results can inform tactile graphics literacy training. By studying how BVI people construct and retrieve from graphical representations, we begin to distinguish forms and exploratory procedures that may improve the access of analytical information of tactile data representations. We hope to continue revising and appending to these initial observations.

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REFERENCES

[1] Fearn Bishop, Johannes Zagermann, Ulrike Pfeil, Gemma Sanderson, Harald Reiterer, and Uta Hinrichs. 2019. Construct-A-Vis: exploring the free-form visualization processes of children. IEEE Transactions on Visualization and Computer Graphics 26, 1 (2019), 451–460.

[2] Jeremy Boy, Ronald A Rensink, Enrico Bertini, and Jean-Daniel Fekete. 2014. A principled way of assessing visualization literacy. IEEE transactions on visualization and computer graphics 20, 12 (2014), 1963–1972.

[3] Braille Authority of North American and Canadian Braille Authority. 2011. Guidelines and Standards for Tactile Graphics.

[4] Carol Castellano. 2006. Making it work: Educating the blind/ visually impaired student in the regular school. IAP.

[5] Julie Ducasse, Anke M Brock, and Christophe Jouffrais. 2018. Accessible interactive maps for visually impaired users. In Mobility of visually impaired people. Springer, 537–584.

[6] Giovanni Fusco and Valerie S Morash. 2015. The tactile graphics helper: providing audio clarification for tactile graphics using machine vision. In Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility. 97–106.

[7] Samuel Huron, Yvonne Jansen, and Sheelagh Carpendale. 2014. Constructing Visual Representations: Investigating the Use of Tangible Tokens. IEEE Transactions on Visualization and Computer Graphics 20, 12 (2014). 2102–2111

[8] Yvonne Jansen and Pierre Dragicevic. 2013. An interaction model for visualizations beyond the desktop. IEEE Transactions on Visualization and Computer Graphics 19, 12 (2013), 2396–2405.

[9] Roberta L Klatzky and Susan J Lederman. 1992. Stages of manual exploration in haptic object identification. Perception & Psychophysics 52, 6 (1992), 661–670.

[10] Giuseppe Melfi, Karin MuÌler, Thorsten Schwarz, Gerhard Jaworek, and Rainer Stiefelhagen. 2020. Understanding what you feel: A Mobile Audio- Tactile System for Graphics Used at Schools with Students with Visual Impairment. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. 1–12.

[11] L Penny Rosenblum, Li Cheng, and Carole R Beal. 2018. Teachers of students with visual impairments share experiences and advice for supporting students in understanding graphics. Journal of visual impairment & blindness 112, 5 (2018), 475–487.

[12] Masami Shinohara, Yutaka Shimizu, and Akira Mochizuki. 1998. Three-dimensional tactile display for the blind. IEEE Transactions on Rehabilitation Engineering 6, 3 (1998), 249–256.

[13] Derrick W Smith and Sinikka M Smothers. 2012. The role and characteristics of tactile graphics in secondary mathematics and science textbooks in braille. Journal of Visual Impairment & Blindness 106, 9 (2012), 543–554.

[14] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In Proceedings of the 33rd annual acm conference on human factors in computing systems. 3237–3246.

[15] Alice Thudt, Uta Hinrichs, Samuel Huron, and Sheelagh Carpendale. 2018. Self-reflection and personal physicalization construction. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. 1–13.

[16] Annie Vinter, Viviane Fernandes, Oriana Orlandi, and Pascal Morgan. 2012. Exploratory procedures of tactile images in visually impaired and blindfolded sighted children: How they relate to their consequent performance in drawing. Research in Developmental Disabilities 33, 6 (2012), 1819–1831.

[17] Suzette Wright. 2008. Guide to Designing Tactile Illustrations for Children's Books. American Printing House for the Blind.