Refreshable Tactile Displays – Research to Help Guide Reform to Tactile Graphics Access

by Leona Holloway1, Matthew Butler1, Samuel Reinders1, Peter Cracknell2 and Kim Marriott1

1 Faculty of Information Technology, Monash University, Australia

2 Quantum RLV

# 1. Introduction

Dynamic or Refreshable Tactile Displays (RTDs) are devices with a grid of dots that can be raised or lowered to represent braille and tactile graphics. While RTDs have been available in various forms for some time, it is only recently that they have moved from the realm of research and toward consumer use. This is by virtue of practical form factors, integration with widely used technologies, and the potential for wider affordability. RTDs promise dynamic generation and unprecedented access to tactile graphics, however with limitations in terms of resolution and visual contrast. This radical change in the way in which tactile graphics will be accessed requires the accessibility community to rethink our practices in terms of the design and distribution of tactile graphics.

The Inclusive Technologies team at Monash University works collaboratively with the blind and low vision (BLV) community to research accessibility solutions using new technologies. With the emergence of consumer RTDs, we recognise the need to reflect on current tactile graphic guidelines and consider them in the context of the characteristics of RTD, as well as exploring the exciting new affordances that they bring.

This paper will present an overview of the current state of consumer-level RTDs, and most importantly identify the key design and research challenges that must be addressed for their most effective use and to increase the likelihood of wider consumer adoption. To do this, a number of key examples will be presented where RTDs have been explored. Within each example, motivations will be described, links to design and research challenges presented, and key learnings identified.

As such, this paper seeks to make the following contributions:

* Identifying the ongoing design challenges for the adoption of RTDs as meaningful tools for the delivery of tactile materials.
* Presenting practical case studies of the use of RTDs and highlighting the key findings to date, including preliminary implications for design.

# 2. The Current State of RTD Technology

A range of RTD hardware devices are now available, each with different capabilities and affordances. The most relevant devices in the consumer market in 2024 are the DotPad, the Monarch and the Canute. All have a fixed dot height and spacing similar to that of the braille cell.

The DotPad by Dot Inc. is the smallest (274×229×31 mm) and lightest (1.2 kg) RTD currently available. It has a grid of 30 cells in 10 rows with an accompanying 20 cell braille line. The DotPad does not have a keyboard or braille keys for data entry, nor an onboard computer, but rather acts as a display for a connected device, such as an iPad or laptop. The first software for the DotPad is a drawing app called DotCanvas that transmits braille and graphics to the DotPad display. Whole page panning of graphics is possible, but not incremental panning. Whole page labels can be attached to diagrams and displayed either on the braille line or as audio output.

The Monarch by Humanware is the largest device (404 x 267 x 36 mm) and weighs 2.1 kg. It has a grid of 32 cells in 10 rows. A braille keyboard allows for data entry and editing. The Monarch has an onboard computer with bespoke apps for multi-line braille text, displaying diagrams, drawing and mathematics. The device is touch-sensitive and cursor routing to individual cells is possible, as are audio annotations at individual points. Incremental panning and zooming of large graphics is possible.

The Canute by Bristol Braille is the heaviest device (3.1 kg), not including the power supply. The dimensions are (356×178×38 mm) and it has 9 rows of 40 cells. The Canute has a fixed separation between rows which limits its use as a graphics device. It has no onboard computer or keys for data input. Though the Canute cannot display conventional dot graphics, their designers have been working on innovative solutions, for example using braille letters as fill patterns for horizontal bar graphs and on maps.

The above devices are all still in development and or have only recently entered the commercial market. Most of the research to date has therefore been conducted using earlier devices such as the graphics devices by Metec and the Graphiti by Orbit Research. Metec devices have closely spaced pins and are available in a range of sizes. The Graphiti has a display of 40 x 60 widely spaced pins that are unique in their ability to be raised to four different heights. Both devices are touch-sensitive.

# 3. Key Research Challenges

With a focus on the use of RTDs for access to data visualisations, we recently consulted with key stakeholders – blind touch readers, vision specialist teachers, accessible format producers and assistive technology providers – to explore the potential uses, advantages and areas for development [8]. This work revealed excitement regarding key possibilities of RTDs, including:

* **Dynamic Content:** RTDs introduce the possibility of tactile animations.
* **Timeliness:** RTDs potentially afford the ability to have automated images and data produced and displayed instantaneously. This will allow BLV students to access information at the same time as their peers in the classroom.
* **Immediate Feedback & Corrections:** RTDs will allow accessible format producers to check, receive feedback from end users, and edit accessible graphics in real-time.
* **User Creation:** RTDs allow BLV people to be creators, rather than just passive receivers of data visualisations. This will enable a transfer of power from the producer to the user.

The work also highlighted a number of research challenges that need to be addressed before the full potential of RTDs can be realised.

**RC1:** The potential **applications and context of use** for RTDs are not yet clear, with more research required. To date, education and mapping have received the most attention (e.g. [1, 4, 13]) but there are also other potential applications for RTDs in the workplace, such as in the workplace for accessing productivity applications like spreadsheets or presentation software.

**RC2: Design of graphics** for display on RTDs. These new devices introduce unique design attributes such as the number, arrangement and height of pins and the possibility of zooming and panning. This necessitates a new way of thinking about the design of tactile graphics, with a potential need for RTD-specific design guidelines.

**RC3: Taking advantage of the dynamic nature of RTDs**. RTDs enable animation, zooming, showing sequences of graphics with increasing complexity/detail, and highlighting using blinking pins. Some early research has confirmed that large tactile images can be understood by blind users via zooming and panning [5, 12] and our research indicates the usefulness of animation, highlighting, and gradually adding details to build complexity [7]. RTDs could also allow access to dynamic data displays, for example showing sailing speed, wind direction and compass bearing on a boat in real-time. However, further research is required to determine the most appropriate way to support interactions with dynamic content, optimal hand movements for reading tactile graphics with moving components, and issues relating to maintaining a mental model when the graphic changes.

**RC4: Multimodal interaction and interfaces.** Digital presentation, in particular on touch-sensitive RTDs, enables the use of audio labels and sonification (e.g. [16]). Currently it is unclear how to best support this. Conversational agents offer another exciting possibility for supporting interactions with RTDs. While this combination has been explored for 3D models [14], it has not been addressed in the context of RTDs.

**RC5: Authoring.** With a new format for the presentation of tactile graphics comes the need for new authoring tools and methods. In particular, there is much interest tools in tools that can support nonvisual image creation by end users [3, 11] and quick creation by teachers in the classroom without needing specialist knowledge [8]. Creation might be manual or automatic generation of graphics from data. Recent advances in generative AI potentially offer radically new ways to support authoring [9].

**RC6: The design of RTD hardware and software** is a major issue that underpins all of the above research challenges. As we have seen, the RTDs coming onto the market each have markedly different characteristics generally reflecting different cost/feature tradeoffs. We do not yet have an understanding of the “sweet spots” in this design space. For example, while there is some research on the topic (e.g. [6]), we do not yet understand the impact that the spacing of pins has on perception or the trade-offs between larger more expensive displays and cheaper displays with fewer pins but with zooming and panning. Another difference is whether the pins can be raised to different heights. Initial testing suggests that pin height is a valuable way of distinguishing between regions on an RTD but that care needs to be taken to ensure the different heights are distinguishable [7].

There are also questions about refresh rate and directions of refresh and how these impact the perception of movement in animated graphics [7]. Another significant difference is whether the tablet tracks touch and supports touch gestures, and if it does support touch gestures whether this is multitouch or single finger only.

The design of cheaper RTDs is an ongoing issue [2], especially for adoption in the home market and in poorer economies.

# 4. Key Example Projects

This section provides an overview of RTDs research conducted by the Inclusive Technologies team at Monash University. This work provides some initial insights into the key research challenges defined above.

## 4.1 Tactile Animations

In a study conducted in 2022, we investigated the use of RTDs for displaying animated tactile images [7]. The work began with a survey of 19 touch readers and seven accessibility experts, revealing a high interest in tactile animations. Animations providing learning support for children and information for adults such as maps were ranked as more important than sport and entertainment applications (RC1).

We next created a range of animations, or image series, depicting some of the most popular requests from the survey. A transcriber created the diagrams manually for optimal presentation, with dot-by-dot editing required for any images that were imported from another format (RC5). The diagrams were displayed on a Graphiti refreshable display and the four pin heights were very helpful for a number of purposes: to distinguish between more and less important features (e.g. tall graph lines and lower grid lines); in the place of texture or colour to distinguish between different areas (e.g. tall tree roots against low soil); and to indicate depth (e.g. protruding or receding limbs on a dancing figure, and buildings as the tallest features on a city map) (RC2). The use of multiple pin heights allowed a surprising amount of detail to be conveyed on the low-resolution grid of 60 by 40 pins. However, effectively only three heights (0.5 mm, 1 mm and 2 mm) could be used to convey meaning, with 1.5 mm height easily being confused with the other heights (RC6).

The animations were co-designed with a touch reader and then the four most successful animations were evaluated by 12 blind adults alongside equivalent tactile graphics. Overall, the RTD was more successful than a sequence of tactile graphics in conveying change and giving a sense of movement.

With a slow refresh rate requiring up to 5 seconds for the whole display, animations worked best when the change was in small steps, confined to a discreet section of the display and following the same direction as the refresh. For example, a waterfall moving downwards worked well with pins refreshing from the top to the bottom of the display, but a bird with large wings flapping upward resulted in some moments when two sets of wings were visible at once, causing confusion.

Dynamic authoring provided unexpected advantages for the RTD over tactile graphics during the study (RC3). When errors were found, users needed the diagrams to be simplified or changes were suggested, updates could be made very quickly using the RTD in contrast with the swell paper graphics, which could not be corrected offsite away from the necessary equipment. Dynamic authoring or the use of a blinking cursor or drawing line could also be used to direct attention on a diagram, for example showing a walking route on a map, without having to use hand-over-hand technique.

Thus, this study revealed interest in and the utility of RTDs as a new mechanism for showing dynamic content as tactile graphics, however there were trade-offs in terms of resolution and textural properties. Much more research and development is needed into the optimal design of both RTDs and the graphics that they display.

## 4.2 Increasing Access to Data Visualisations By Combining RTDs with Conversational Agents

We are currently investigating how RTDs can be combined with conversational agents to increase access to data visualisations. The use of conversational agents, like Siri, Alexa or Google Assistant, to enhance interaction with RTDs has not yet been previously considered, and could help address issues of equity when it comes to access to, and interaction with, data visualisations (RC4).

To do this, we are conducting a Wizard-of-Oz study with a Graphiti refreshable display. Wizard-of-Oz is a research experiment where an end user interacts with an interface that is operated by a “wizard” who fulfils interaction functionality that is yet to be fully implemented [10]. This method allows us to observe the ways in which BLV users would choose to naturally interact with a system that combines an RTD and conversational agent for accessible data access and analysis.

As of March 2024 we have worked with 11 BLV touch readers who have used touch combined with voice commands to interact with a range of different visualisations such as line graphs, bar charts and heat maps. We have found that participants often begin with tactile exploration of the visualisations rendered on the RTD, then expect to be able to use combinations of touch gestures or direct spoken interactions with the conversational agent (the wizard) in order to ascertain details or validate finer details, for example confirming a specific value.

Once complete, this work will provide a solid basis for the design of a future system that will combine touch sensitive RTDs and conversational agents for the purpose of facilitating accessible access to data. More widely, it may lead to design considerations for future RTDs, where they have the ability to formally integrate with standard conversational agents such as Siri or Alexa, or are built directly into the RTDs themselves.

## 4.3 Mathematics Education

The role of RTDs for mathematics is an emerging area and potentially one of the key application areas (RC1). The global mathematics curriculum relies on graphics, including bar charts, line charts, scatter plots, graphs of mathematical functions, trigonometry diagrams, network diagrams, tables and matrices. BLV students are typically provided with equivalent raised line drawings or written/verbal descriptions, however these come with limitations. Descriptions inevitably leave out details for more complex graphics and do not allow the student to form an independent understanding of the graphic. Tactile graphics support independent exploration but high quality diagrams must be created by trained transcribers using specialist equipment, limiting timely access and the amount of spontaneous learning activity that can take place, such as the interactions that often occur between the student and teacher, or the student and their peers. Alternatively, tactile graphs can be created in the classroom by the BLV student or an aide using tactile grids and tools but the resultant graphics are temporary in nature.

Automated generation of mathematics graphs using RTDs (RC5) has been an early area of research [1, 15]. This work has focused on the creation of interfaces between accessible maths software and RTDs, in the attempt to provide tactile access to the outputs of the maths software. The importance of supporting mathematics is also recognised by developers of RTDs, with the Monarch device explicitly integrating graphing calculator functionality. Given the dynamic nature of RTDs, other devices could also support workflows such as those developed by Albert [1] and Schwarz and colleagues [15] that allow for the provision of graphical maths content. Ideally, such mathematics authoring software would be open source and able to be used across different RTD devices (RC6).

It is here that this work has overlap with the work being undertaken related to data visualisation. In both [1] and [15], the work explores not only representation of graphical mathematics content, but also interactions by the touch reader. These include: finding coordinates and areas of interest, including the use of “flashing” pins; selection; zooming; panning; and general navigation (RC3). Ongoing work needs to explore these interactions, to understand how RTDs can support natural and well-understood interaction strategies (e.g. pinch to zoom), but also what new gestures are required to be developed to support meaningful interaction (RC4).

The often multi-line nature of mathematics notation also presents a strong use case for RTDs in the mathematics context (RC1). Equations often flow over more than one line, therefore by using an RTD, a touch reader can explore two parts of an equation at once. Similarly, an RTD may be crucial for best presenting notations where layout is critical, such as in spatial arrangement of addition and subtraction for young learners, or matrices for senior mathematics.

Given the above affordances, RTDs may also be able to support greater inclusiveness and collaboration between students and their peers and teachers in the classroom. With the ability to interface with accessible mathematics software and to produce output on RTDs that is accessible both tactually and visually, it could be easier for BLV students to work with teachers and peers with shared representations of content (RC5). This can only support stronger learning outcomes. As such, this is a key area of future research.

# 5. Conclusion

RTDs have the potential to transform the availability of braille and tactile graphics. However, their successful adoption relies upon the development of optimal devices, software and processes. In this paper, we have highlighted six key research challenges: (RC1) Identifying the most important usesfor RTDs; (RC2) developing new design guidelines specifically for tactile graphics to be displayed on RTDs; (RC3) determining the most appropriate way to support interactions with dynamic content; (RC4) exploring the role of multimodal interactions and interfaces; (RC5) developing new authoring tools and methods; and (RC6) designing the necessary hardware and software to support these challenges. Now is the time for researchers, producers, touch readers and technology companies to work on these research challenges together as a community so that we can help to drive future developments to fit our needs.

# 

# References

[1] Albert, P. (2006). “Math Class: An Application for Dynamic Tactile Graphics”. ICCHP: International Conference on Helping People with Special Needs, Linz, Austria.

[2] Bhatnagar, T., Higgins, A., Marquardt, N., Miodownik, M., & Holloway, C. (2023). “Analysis of Product Architectures of Pin Array Technologies for Tactile Displays”. Proceedings of the ACM on Human-Computer Interaction, 7(ISS), 135-155.

[3] Bornschein, J., Bornschein, D., & Weber, G. (2018). “Comparing Computer-Based Drawing Methods for Blind People with Real-Time Tactile Feedback”. CHI Conference on Human Factors in Computing Systems, Montréal, QC, Canada.

[4] Brayda, L., Leo, F., Baccelliere, C., Ferrari, E., & Vigini, C. (2018). “Updated Tactile Feedback with a Pin Array Matrix Helps Blind People to Reduce Self-Location Errors”. Micromachines (Basel), 14(9), 351.

[5] Ducasse, J., Macé, M. J.-M., Oriola, B., & Jouffrais, C. (2018). “BotMap: Non-Visual Panning and Zooming with an Actuated Tabletop Tangible Interface”. ACM Transactions on Accessible Computing (TACCESS), 25(4), 1-42.

[6] Garcia-Hernandez, N., Tsagarakis, N. &Caldwell, D. (2011). “Feeling through Tactile Displays: A Study on the Effect of the Array Density and Size on the Discrimination of Tactile Patterns”. IEEE Transactions on Haptics, 4(2), 100-110.

[7] Holloway, L., Ananthanarayan, S., Butler, M., De Silva, M., Ellis, K., Goncu, C., Stephens, K., & Marriott, K. (2022). “Animations at your Fingertips: Using a Refreshable Tactile Display to Convey Motion Graphics for People who are Blind or have Low Vision”. ASSETS International ACM SIGACCESS Conference on Computers and Accessibility, Athens, Greece.

[8] Holloway, L., Cracknell, P., Stephens, K., Fanshawe, M., Reinders, S., Marriott, K., & Butler, M. (2023). “Refreshable Tactile Displays for Accessible Data Visualisation”. Poster presentation at IEEE VIS: Visualization & Visual Analytics, Melbourne, Australia.

[9] Huh, M., Peng, Y.-H., & Pavel, A. (2023). “GenAssist: Making Image Generation Accessible”. UIST '23: The 36th Annual ACM Symposium on User Interface Software and Technology, San Francisco, CA, USA.

[10] Kelley, J. F. (1984). “An iterative design methodology for user-friendly natural language office information applications”. ACM Transactions on Information Systems, 2(1), 26-41.

[11] Kobayashi, M., & Watanabe, T. (2004). “Communication System for the Blind Using Tactile Displays and Ultrasonic Pens – MIMIZU”. ICCHP: International Conference on Computers Helping People with Print Disabilities, Paris, France.

[12] Lévesque, V., Petit, G., Dufresne, A., & Hayward, V. (2012). “Adaptive level of detail in dynamic, refreshable tactile graphics”. IEEE Haptics Symposium (HAPTICS), Vancouver, BC, Canada.

[13] Petit, G., Dufresne, A., Levesque, V., Hayward, V., & Trudeau, N. (2008). “Refreshable Tactile Graphics Applied to Schoolbook Illustrations for Students with Visual Impairment”. ASSETS International ACM SIGACCESS Conference on Computers and Accessibility, Nova Scotia, Canada.

[14] Reinders, S., Butler, M., & Marriott, K. (2020). "’Hey Model!’–Natural User Interactions and Agency in Accessible Interactive 3D Models”. CHI Conference on Human Factors in Computing Systems, virtual.

[15] Schwarz, T., Melfi, G., Scheiffele, S., & Stiefelhagen, R. (2022). “Interface for Automatic Tactile Display of Data Plots”. Joint International Conference on Digital Inclusion, Assistive Technology & Accessibility (ICCHP-AAATE) Lecco, Italy.

[16] Zeng, L., Weber, G., & Baumann, U. (2012). “Audio-haptic you-are-here maps on a mobile touch-enabled pin-matrix display”. IEEE International Workshop on Haptic Audio Visual Environments and Games (HAVE 2012), Munich, Germany.