Animations at Your Fingertips: Using a Refreshable Tactile Display to Convey Motion Graphics for People who are Blind or have Low Vision

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Figure 1: Touch readers exploring images on a Refreshable Tactile Display

ABSTRACT

People who are blind rely on touch and hearing to understand the world around them, however it is extremely difficult to understand movement through these modes. The advent of refreshable tactile displays (RTDs) offers the potential for blind people to access tactile animations for the very first time. A survey of touch readers and vision accessibility experts revealed a high level of enthusiasm for tactile animations, particularly those relating to education, mapping and concept development. Based on these suggestions, a range of tactile animations were developed and four were presented to 12 touch readers. The RTD held advantages over traditional tactile graphics for conveying movement, depth and height, however there were trade-offs in terms of resolution and textural properties. This work offers a first glimpse into how refreshable tactile displays can best be utilised to convey animated graphics for people who are blind.

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CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in accessibility**; **Accessibility technologies**; *Accessibility systems and tools.*

KEYWORDS

blind, tactile graphics, refreshable displays, accessible graphics

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1 INTRODUCTION

A recent resurgence in refreshable tactile displays (RTDs) with larger tactile surfaces offers new opportunities for the touch reading community. Along with the obvious advantages of storage space, reduction of hard copy materials and immediate access, RTDs offer the brand new possibility of **animated tactile images**. Until now, if you were blind or had low vision (BLV), access to dynamic graphics such as an animation showing how a bird flaps its wings was provided by a sequence of tactile graphics, with successive graphics showing key frames in the animation. Tactile animations offer an exciting alternative.

While there has been considerable research into technologies for building refreshable displays, e.g. [44, 72], there has been little research into the usefulness and effectiveness of animated tactile images for presenting dynamic graphics to BLV people. Prior research has focused on specific applications–a blind soccer match [37, 54], fireworks display [62, 63] and zooming/panning on a map [75, 76]. Here we investigate the effectiveness and design of animated tactile images *in general*. Our specific contributions are threefold:

Contribution 1: Identification of potential application areas and diagrams that touch readers would like to see displayed as animated tactile images on RTDs. As a first step we conducted an online survey of 19 touch readers and seven accessibility experts asking what animated tactile images would be of interest to touch readers. This revealed a high level of interest in animated tactile images. Learning support for children and information for adults were ranked as more important than sport and entertainment applications.

Contribution 2: Design considerations for creating animated tactile images for touch readers. The research team, one of whom is blind, collaboratively designed a variety of animated tactile images. These were tested on a Graphiti RTD[1]. Design considerations include taking account of the lower resolution of most RTD displays, and tailoring the refresh rate to the complexity of the image. A limitation of the Graphiti display (like many RTDs), is a slow refresh rate of up to 5 seconds for a full page. This meant that the animations are generally experienced as a sequence of discrete frames rather than as fluid animations.

Contribution 3: Comparison of animated tactile images with a sequence of tactile graphics. We conducted a user study with 12 BLV participants comparing animated tactile images shown on the Graphiti versus traditional tactile graphics. We presented four image sequences in both formats. Overall, participants were better able to understand change and gain a sense of movement using the RTD and drew parallels to animation and movies. However, tactile graphics were generally preferred for understanding of a static diagram due to higher resolution and superior textural and colour contrast. An unexpected advantage of RTDs over traditional tactile graphics is that images can be immediately modified in response to viewer feedback.

The research presented here is a first step in exploring the potential of tactile animations. We hope that it motivates greater exploration of this new media for touch readers. Our findings provide guidance for future designers creating content for touch readers on RTDs. They also provide guidance on the design of future RTDs, suggesting that increasing the refresh rate is less important than increasing the resolution.

2 RELATED WORK

2.1 Animated Graphics

There are three standard approaches to visually showing change over time. These rely on creating a sequence of frames, each frame a snapshot of the scene at a particular instant in time. The first approach is to arrange the frames temporally. This results in an animated graphic in which the frames are shown to the viewer, one after another. Typically the frames are shown in rapid succession so that the viewer's visual system does not perceive the individual frames but rather perceives objects to be moving smoothly. In the second approach, called small multiples, selected frames are arranged spatially in a sequence or grid. In the third approach, a few frames may be overlaid and arrows or other annotations used to show the direction of movement.

There have been many studies comparing the effectiveness of instructional materials showing change over time using animation with those using small multiples [7, 11, 33, 70]. The results are mixed. The disadvantage of an animation is that it is difficult to track multiple simultaneous changes and that if the viewer wishes to compare two frames they must remember one of those frames and mentally compare it with the current frame. On the other hand, it seems to be easier to track selected objects if the surrounds are also changing in an animation [5]. There is also evidence that human body movements are easier to learn from an animation than small multiples [7]. Another application in which animation has proved effective is to animate transitions between different views of the data in data visualisation [30].

2.2 Tactile Graphics

Tactile graphics, also known as raised line drawings, are recommended as the best way for people who are blind or have low vision to access and understand diagrams with spatial information [17, 42, 65]. The first tactile graphics were produced manually using collage and copied using pressed wet paper (e.g. [40]) or thermoforming, and collage remains the most popular technique used by vision specialist teachers in schools [58]. Since the widespread adoption of digital production in the 1980s, swell paper and embossing have become the most popular tactile graphics production techniques [66]. Discriminability of textures and lines are the most important factors determining user preference for tactile graphics, with variable heights and visual contrast as welcome additions [4].

While there are many internationally recognised and detailed guidelines on the design of tactile graphics (e.g. [17, 25, 65]), they provide little or no advice on how to represent moving images. Instead, there is an assumption that tactile graphics will be based on static images, usually from text books. These may use small multiples or annotations like arrows to convey change and movement (Fig. 2a&b). Due to the high storage and/or material costs of some tactile graphics, when a large number of diagrams is required, as with small multiples, they are often reduced in size. This can negatively impact their legibility by touch.

Another approach to movement in tactile graphics, employed mainly for young children, has been the addition of moving parts to a base diagram. For example, a cardboard clock hand may be attached to a tactile graphic of a clock using a split pin (Fig. 2c), or a bead may be attached to a thread placed across the tactile image to denote movement along a route [23, 25]. Whilst providing a high level of engagement, these graphics must be handmade, they are often bulky and they must be stored in hard copy.

[1]http://www.orbitresearch.com/product/graphiti/

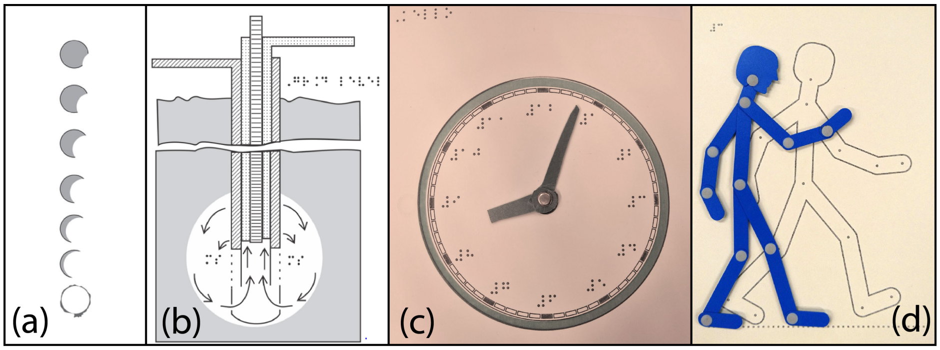

Figure 2: Examples of traditional approaches to conveying movement with tactile graphics: (a) small multiples depicting solar eclipse stages (b) using arrows to signal the movement of melted sulfur during the Frasch process (c) moving parts (clock hands attached with a split pin) on a tactile graphic and (d) a manipulative to accompany a static tactile diagram (Fleximan by Hungry Fingers)

2.3 Refreshable Tactile Displays (RTDs)

Refreshable tactile displays date back as far as 1931 [1], and some such as the Optacon have even been used to covert images to refreshable pins on a small display [19, 22]. Since the advent of maker technologies and an injection of funding spurred by the DAISY Consortium's Transforming Braille Project [69], a range of competing technologies have come to market or are in prototype phase. The majority of refreshable tactile displays consist of a grid of pins controlled by electro-mechanical actuators [72]. Resulting from the HyperBraille project[2], Metec have been selling refreshable graphics displays since 2012[3]. More recently, Orbit Research has released Graphiti, a tactile display of 60×40 refreshable pins that can be raised to four different heights[4]. Looking forward, Humanware is working in partnership with the American Printing House for the Blind to develop a Dynamic Tactile Display (DTD) similar in size to Graphiti and spaced comparably with braille [24]. Meanwhile, Dot Inc is developing Dot Pads, a refreshable pin display with the capability to zoom and pan[5]. Also in development, the Blitab Android Tablet has 14 rows of 23 6-dot braille cells[6] and is designed for displaying both text and images, and TTPAT are developing the TouchPad Pro with dots raising to varying heights and a colour display[7].

Fixed grids of movable pins or braille dots are not the only approach for creating refreshable tactile displays. Some researchers have attached a small grid of pins to a mouse; as the mouse is moved, the pins are updated reflecting the mouse's position on a large virtual grid [41]. Disney Research used water jets on a flexible screen [62, 63]. Surface haptic devices such as the TeslaTouch [9] use electrostatic resistance on a flat screen, however detection is limited to very simple shapes using this method [71].

The touch-feedback feature of tactile displays can also been used to support audio feedback. Researchers have explored the limitations for touch input and made subsequent suggestions regarding the design of refreshable graphics to be used for this purpose [59, 61].

2.4 Applications of RTDs

The most basic research into RTDs examines perception based on pin density, height and other factors like vibration [27, 37, 54]. Initial research into their use has focused on the display of static images in the fields of art [29], maps [18, 34, 43, 51, 67, 75] and textbook diagrams [36, 52, 57]. Most notably, O'Modhrain and colleagues explored the possibilities and potential pitfalls of refreshable graphics displays from the perspective of vision impaired users [55]. They point out that most refreshable tactile displays have low fidelity, therefore images must be simplified and carefully designed to be readable on a refreshable tactile display.

There has also been considerable interest in using RTDs to give real-time feedback to assist people who are BLV when creating graphics. They have been used for drawing [13, 38, 53], plotting mathematical charts [3, 39] and for 3D modelling [47, 68]. Similarly, Bornshein, Prescher and colleagues have investigated the use of touch-sensitive refreshable displays for collaborative creation of tactile graphics [14–16]. The advantages of being able to update graphics or store multiple versions on an RTD have also been explored [18, 43, 45].

2.5 Animated Tactile Images

There has been much less research into the use of RTDs to show change over time by presenting animated tactile images.

Weber and colleagues have investigated zooming and panning of a map and UML diagrams on an RTD [48, 60, 75, 76]. A pilot evaluation suggested BLV participants found it difficult to explore a map using panning [76].

Ohshima, Kobayashi and colleagues developed and tested a system to represent a football match on an RTD [37, 54]. They reported that of their seven participants "several participants commented that they could distinguish the detailed movement of the players" [54]. Jung and colleagues presented animated games like pong

[2] http://hyperbraille.de/project/
[3] https://metec-ag.de/produkte-graphik-display.php
[4] http://www.orbitresearch.com/product/graphiti/
[5] https://pad.dotincorp.com/
[6] https://blitab.com/
[7] https://tppat.com/the-touchpad-pro/

on a small prototype RTD. Users held their hand flat on the device and were able to locate stimuli within a 13mm a margin of error [35].

A range of other methods have also been trialled to create tactile animations. Disney Research investigated the use of their water-jet display for visualisation of fireworks displays, which was evaluated as enjoyable by most of their BLV participants [62, 63]. The Phantom device has been used to haptically explore 3D objects moving in virtual reality, e.g. [10, 47]. Slide-tone and Tile-tone use motors to move a user's finger along a graph line [26] and Robographics uses motorised robots to indicate key areas on a graphic [28]. However, none of these methods are applied to representational tactile graphics.

To date there has not been a systematic investigation of using animations to show change in tactile graphics over time. Here we address three fundamental questions: When and for what types of graphics are they useful? What are design guidelines for creating them? And how do they compare with traditional tactile graphic presentations?

3 CONSULTATION

We began by consulting with the vision impaired community to determine whether tactile animation is of interest and, if so, what type of animations would be of most value.

3.1 Method

A list of possible animations was derived through multiple brainstorming sessions with the research team, cross-referencing against school textbooks, and in consultation with touch readers. This list, as given in Table 1 but with accompanying examples, was presented in survey format. Respondents were asked to indicate which they would be interested in having made available and to provide further examples of tactile animations that they would recommend.

The survey was distributed online using Google Forms. It was tested for accessibility and keyboard shortcuts were provided. The survey link was shared through a participants pool, social media and listservs.

3.2 Participants

A total of 26 people responded to the survey. Nineteen were touch readers and seven were sighted members of the BLV community – parents of touch readers(n=2), accessible formats producers(n=3) and vision specialist teachers(n=3). The average age was 52 years (sd=13.7), ranging from 20 to 75. The vast majority resided in Australia (n=17), with the remainder in North America (n=7) or New Zealand (n=1). There was a reasonable gender balance, with 14 women, 10 men and 1 non-binary. Education level was high, with 17 respondents (68%) holding a Bachelor's degree or higher, compared with 24% of the Australian adult population in 2016 [6]. Of the touch readers, 16 were totally blind and 2 were legally blind. Twelve were blind from birth and two had acquired their vision impairment at age 15 or over. The majority of the touch readers (n=12) considered themselves up-to-date with new technology and a further five were early adopters. Overall, the self-selected sample are well-educated and technology savvy, potentially representing the future early adopters of RTDs. However, it is acknowledged that the respondents are not a homogeneous group, potentially differing in their priorities.

3.3 Results

As shown in Table 1, there is a high level of interest in moving tactile images. In general, learning support for children and information for adults were seen as more important than sport and entertainment applications. More specifically, the most popular selections were **astronomy** (e.g. planetary orbits, eclipse, the big bang), **geographic movement** (e.g. shifting of the continents over time, tectonic plate movement, erosion, waves), **maps** with movement along a route, **rotation** (e.g. geometric shapes rotating, the earth spinning), **biology concepts** (e.g. plant growth, embryo growth, mitosis and meiosis), **physics animations** (e.g. projectile motion, pulleys, pendulum movement, airplane wings), **maps with movement** in space (e.g. stage directions, dance positions, etc.) and **human movement** (e.g. dance moves, exercise moves, sports moves, swimming strokes).

In addition, participants made a number of further suggestions for moving graphics for **education** (analogue and digital output from oscilloscopes, plotters and curve tracers; CAD/CAM software for schematics and CNC machining work; chemical reactions; dynamic charts for maths and statistics; historical maps; sex education), for **orientation and mobility** (transport routes with movement), **sports** (team sport positions; martial arts), for **entertainment** (movies, tv or videos), and to assist with **content creation** (videos; presentation slides). Some further suggestions were given for static images.

4 INITIAL DESIGN EXPLORATION

4.1 Graphiti

Figure 3: Graphiti tactile display consisting of 60×40 refreshable pins, showcasing an ocean wave

The test images were presented using a Graphiti tactile display, commercially available from Orbit Research [56] for USD$25,000.

Table 1: Interest in moving diagrams by survey respondents who are BLV and others (parents, educators and accessible format producers

Suggested topic	BLV (n=19)	Others (n=7)	Total (n=26)
Education and science			
Astronomy	18	7	25
Geographic movement	17	6	23
Rotation	16	5	21
Physics animations	15	5	20
Biology concepts	15	5	20
Orientation & Mobility			
Map with route	17	7	24
Map with movement	15	6	21
Traffic movement	15	4	19
Concept development			
Modes of flying	16	5	21
Human movement	15	6	21
Animals in motion	14	5	19
News and information			
Weather	14	6	20
Emergency mapping	14	5	19
Disease transmission modelling	11	4	15
Migration patterns of people or animals	10	4	14
Entertainment and games			
Simple computer games	10	7	17
GIFs	7	6	13
Sport			
Players and ball on a football field	9	5	14
Players and ball on a tennis court	8	6	14
Race on a straight track	8	4	12
Race around a circuit	7	5	12

The Graphiti device measures 29.5×26.9× 4.1 cm and provides an array of 60 (horizontal)×40 (vertical) refreshable pins spaced 2.1 mm apart (Fig. 3). Each pin can be raised to one of four heights (0.5 mm, 1 mm, 1.5 mm, and 2.0 mm) allowing images to be displayed in relief. The pins are noticeably larger than standard braille dots.

Below the tactile display, the Graphiti has eight input keys, a space bar, and a navigation pad with four directional buttons (up, down, left, right) along with a select button. These controls were not used in our study as the images were loaded through a HDMI connection to a host PC.

The frame rate on the HDMI connection can be configured to display an image every 1 to 15 seconds. Each line of the image refreshes progressively from the top down. Up to five seconds are required for a refresh, but usually less as only the pins being raised or lowered are refreshed.

4.2 Creation of Sample Graphics

We began by creating a broad range of image sequences to experiment with how best to design images for an RTD and confirm which types of graphics might work best as tactile animations (Fig. 4). All graphics were created in accordance with tactile graphics standards (e.g. [17, 65]) by Holloway, an experienced tactile graphics producer. A range of different software programs were used to create and edit the graphics: Graphiti PC Utility, AseSprite, LibreSprite, Excel, Adobe Illustrator and MS Paint. For each sequence of RTD images, corresponding tactile graphics were created using capsule paper or collage as these techniques are most popular in production houses [66] and schools [58].

These test images were explored by Stephens, who is blind and a competent touch reader. Improvements to the graphics were made as a result of her feedback, for example simplifying or enlarging. As described by O'Modhrain, we found that the low fidelity of the RTD means that graphics must be greatly simplified [55].

4.2.1 Map with Route. One of the first test images was a map of the route to our workplace. A few methods were trialled to dynamically show movement along the route (Fig.4f). The favoured option was to show the full route on the base map then move a single-pin blinking cursor alongside the route as it was verbally described. This allows a touch reader to follow the description but also to independently explore the route. Using the blinking cursor to draw attention was preferable to the invasive practice of hand-over-hand direction of touch [21]. We were also able to use the blinking cursor to aid discussion of other landmarks and routes not already marked

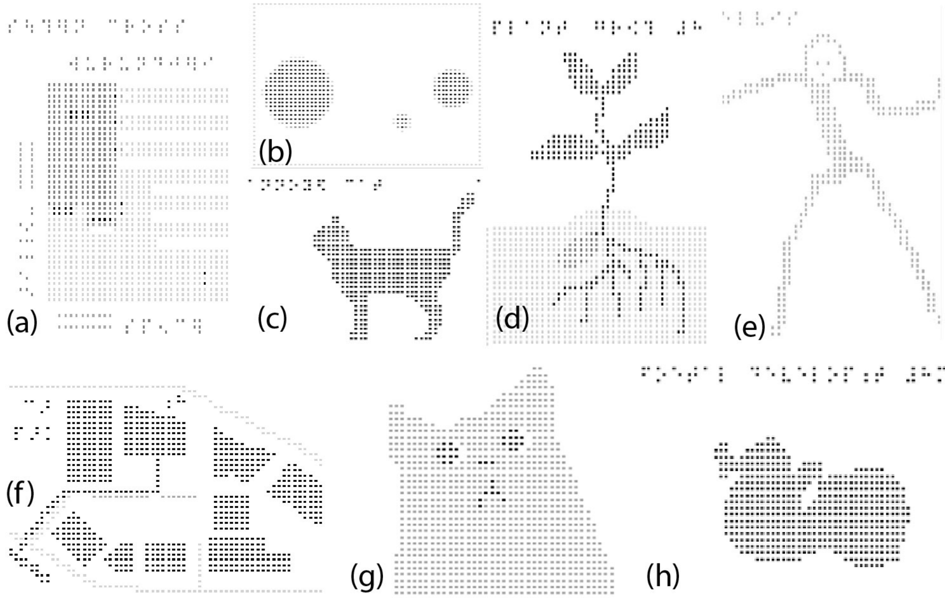

Figure 4: Some of the sample graphics created for presentation on an RTD in the development phase: (a) map of a complex multi-level train station (b) alignment of the sun, earth and moon prior to a solar eclipse (c) cat twitching its tail (d) plant growth (e) Elvis Presley dance moves (f) workplace map (g) cat with moving eyes (h) fetal development. With the exception of the maps, each graphic is part of a sequence of images to show movement or change.

Figure 5: Input images (top row) and RTD images (bottom row) representing a gull in flight. This sequence was very difficult to understand by touch.

on the map. This aligns with prior work finding that blinking pins were the best method of highlighting a static route and important landmarks on a map presented on an RTD [34].

4.2.2 Birds in Flight. Two attempts were made to illustrate a bird in flight. Firstly, a flying gull was depicted in profile view in a sequence of four images (Fig. 5). However, the concept was not conveyed successfully as there was a big change in wing position from one image to the next. This was exacerbated by a slow refresh rate from the top to the bottom of the page, such that the gull may have two sets of wings during the refresh. Moreover, even though the wings were shown at a higher level than the body, it was difficult to distinguish them when held in line with the body.

A second attempt depicted an owl in flight, seen from the front. This eliminated the problem of occlusion, however it was difficult to understand the horizontal spreading of the wings when they were beating down compared with the folding of the wings when they were lifting upwards. The number of images in the sequence was greatly increased to a total of 10 per wing cycle, allowing the sequence to be viewed at a faster rate without the refresh direction causing confusion. The size of the image was also reduced so that the full width of the wings could more easily be felt under the hands and the refresh was faster.

4.2.3 Human Movement. Two sets of diagrams were created to demonstrate human movement. The first illustrated sequential poses of Elvis Presley dancing (Fig. 4e). It provided a good impression of the dance moves that Stephens had heard about but not understood until seeing it on the RTD.

While Elvis Presley's dance moves were interesting, they served purely as entertainment. We next considered human movement for instructional purposes, creating a series of six diagrams to illustrate the moves in a Tai Chi sequence. After some experimentation, we chose to show the eye(s) and nose on the face to give an indicator of the direction of the head; raised dots (buttons) down the centre front of the body to show its direction; and limbs shown with lower dots if they were further away than the body or higher dots if they were closer than the body (Fig. 9). This representation was successful and Stephens liked being able to look at the pose, try it herself and get verbal feedback regarding any minor adjustments that were required. This was much preferred over having someone try to fully describe the poses or physically guide her into the correct positions.

4.2.4 Solar Eclipse. Astronomy was the most wanted requested application for moving tactile images in our survey. To represent a solar eclipse, we began with a representation of the light from the sun, which was blocked by the path of the moon over a series of 26 steps shown in quick succession. While this sequence gave an adequate representation of the phenomenon of a solar eclipse, it did little to explain the causes. We next produced an 8-image sequence depicting the movement of the earth around the sun (slowly) and the moon around the earth (more quickly) up to the point where the moon blocks the light of the sun in a solar eclipse (Fig 4b). When used together, the two diagram sequences enabled a good understanding.

4.2.5 Science. Growth and change through time are a common topic of inquiry in science, especially biology and earth sciences. To depict plant growth from a seed, we began with a horizontal (landscape) alignment, however it was difficult to show all of the important details so we turned the image (and RTD) on its side to portrait orientation to use more of the display space. The soil was initially depicted as low dots but it was difficult to distinguish from the seeds and roots, so the diagram was simplified to show only the line of the top of the soil. This greatly improved contrast and understanding.

The formation of a wave was configured for the RTD as a series of seven diagrams with the water represented as the highest level dots and the sand at level 2. A row of blank dots was reserved between the water and the sand to aid tactile distinction. A single wave changed shape and moved from the ocean on the left to the beach on the right in each successive diagram (Fig 6).

The formation of a waterfall over time was based on a series of five simple print graphics that could be translated quite closely on the RTD. Water was shown as level 1 dots, hard rock as level 4 and soft rock as level 3. Once again, a row of blank dots was reserved between elements to assist with tactile distinction (Fig. 7.

Both the wave and waterfall formation series were considered highly successful – they were simple to understand and the movement was easy to follow, in part because it followed a predictable path in a discrete area of the display.

Stephens requested a representation of human fetal development, thinking that it might be useful for blind parents. However, as the baby curls up in the later months it was impossible to distinguish the limbs (Fig 4h). Refinement of the images using different dot heights may have helped to some extent.

4.2.6 GIFs. Two of the original test images were animated GIFs from social media–one of a cat looking from side to side (Fig. 4g), and another of a cat twitching its tail (Fig.4c). They were selected for trial because the movement was simple and fast. However, while the graphics themselves were clear, the purpose of the GIFs to convey emotional states (puzzlement and annoyance) was unsuccessful because touch readers have a more limited visual vocabulary. Very simplified facial expressions may be easier to understand, and therefore more in keeping with the original intention of GIFs.

4.3 Learnings

4.3.1 Capitalising on Height to Convey Information. Several of the diagrams were unsuccessful on the RTD due to a difficulty in distinguishing between different areas of the diagram, such as the wings on the gull, the eyes on the cat and limbs on the fetus. The gull was produced using standard image software then converted automatically by the Graphiti software. Direct editing of the individual pixels and their heights may have given a better result. Likewise, the fetus diagrams could have been improved with greater use of contrasting heights, with level 1 for the base shape and level 3 or 4 to highlight the the most important features.

4.3.2 Resolution. The low resolution of the RTD meant that less detail could be included in a single RTD diagram compared with a tactile graphic. For example, more braille labels and an additional feature (stairs) could be included on the tactile graphic version of a city square map. Furthermore, curved shapes were difficult to convey with a fixed pin matrix, and prior research has found that tactile shape recognition is worse for pins compared with continuous lines [27].

4.3.3 Refreshing from the Top of the Page. The Graphiti display refreshes its pins progressively from the top row to the bottom. This affected reading of the graphics. Stephens' favourite graphic sequence depicted the formation of a waterfall, beginning with water running from left to right along the top of the display then dropping further down as the ground erodes. She was able to follow the water as the waterfall dropped downwards. Conversely, she had a lot of difficulty interpreting a side view graphic of gull in flight because when the wing was raised, the previous wing was still visible while the display was refreshing. Images that changed from side to side, such as a wave forming from left to right, were less impacted by the refresh from top to bottom. When using RTDs that refresh line-by-line, the refresh direction is a limiting factor and design consideration for the display of sequential images.

4.3.4 Procedure for Presenting Moving Images on a Refreshable Tactile Display. A procedure for best presenting moving tactile images was developed through trial and error while exploring prototype image sequences with Stephens. Guidelines for teaching with tactile graphics state that an overview should be given first [4, 23, 31]. Accordingly, we began by giving a brief but precise verbal description of the first graphic in the sequence, beginning with an overview and then giving the location and height of the key features.

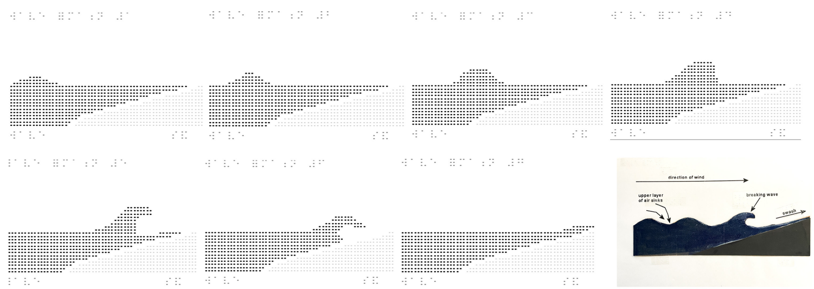

Figure 6: Sequence of seven graphics illustrating the movement of a wave for presentation on a refreshable tactile display, progressing from top left to bottom right, and equivalent collage tactile graphic

5 EVALUATION

In order to better understand the relative benefits and considerations for using an RTD for tactile animations, we ran a user study comparing RTDs with traditional tactile diagram representations.

5.1 Materials

Four tactile animations were selected for the user study. They represented the most popular topics from the online survey and showed a range of different applications. Each image sequence was also produced as corresponding tactile graphics, created in a manner that was considered to be typical of standard practice to provide an ecologically valid comparison. Descriptive text to accompany the graphics was scripted and kept as consistent as possible between the two presentation modes (Appendix A).

5.1.1 Wave. The formation and movement of a wave was based on a print graphic showing a cross-section of the ocean and sea bed with several waves on a single diagram. As described in Section 4.2.5, this was translated to a 7-image sequence of a single wave moving towards the beach on the RTD for the sake of simplicity and because each individual image has no associated material costs. The tactile graphic could show more detail in one diagram and was therefore based much more closely on the original print graphic. It was constructed using collage with water represented using blue cardboard covered in a smooth clear plastic, and sand represented with a fine-grained sandpaper. The wave formation test materials (Fig. 6) were chosen for the user study because the RTD animation was thought to give a good sense of movement and animation.

5.1.2 Waterfall. Waterfall formation was chosen for the user study because it was thought to be a successful example that gave a fairly straightforward translation of educational materials. The corresponding tactile graphics were likewise very similar to the original print graphics. They were created on five separate A4 sheets of swell paper with water represented as horizontal lines, hard rock as solid fill and soft rock as a textured fill. The test materials are shown in Fig. 7.

5.1.3 Map. A new map was created to represent Federation Square, a complex and well-known outdoor area. Buildings were shown as high (level 4) dots and the roads were represented as low (level 1) dots. Space allowed for only two braille labels. The route was not shown on the base graphic, but instead represented by a moving cursor. The corresponding tactile graphic was produced on A4 size swell paper with straight lines for roads and solid filled areas for buildings. Due to the higher fidelity of swell paper, there was enough space to include two additional street names and striped areas for stairs. The route was shown as a dotted line created with a spur wheel. The test materials are shown in Fig. 8. A map was included in the user study because it is one of the most common types of graphics used by people who are blind or have low vision and because it allowed us to explore the use of a flashing cursor as a different means of conveying movement on an RTD.

5.1.4 Tai Chi. As described in Section 4.2.3, a series of diagrams were created to represent a series of Tai Chi movements. The diagram was shown sideways (in portrait) on the RTD to allow details such as the facial features and shirt buttons to indicate rotation. The corresponding tactile graphics were created on swell paper, with the addition of spur wheel lines for the shirt buttons. Three figures were able to be placed on each page, albeit at a smaller size than on the RTD, and limbs were shown with a dashed line if they were further away than the body. We began with a sequence of six diagrams, however after showing them to the first two participants, we realised that this number was unnecessary and time-consuming to interpret, so the number of diagrams was reduced to three for the remaining participants. The test materials are shown in Fig. 9.

5.2 Participants

A total of twelve blind adults took part in the user evaluations, as detailed in Appendix B. Aged from 23 to 68 ($\bar{x}$=46.9), half were totally blind and half were legally blind. Seven had past or present visual experience that they could draw upon to understand visual concepts, including three participants who had enough residual vision to assist in their understanding of the high contrast tactile graphics. All were braille touch readers. While none of the participants used tactile graphics more frequently than monthly, only four considered themselves beginner users needing support in the use of tactile graphics. The remainder considered themselves proficient (n=3) or expert (n=5) in exploring and interpreting tactile graphics. The majority (n=10) considered themselves up-to-date with technology, while one was an early adopter and one needs support or encouragement to try new technologies.

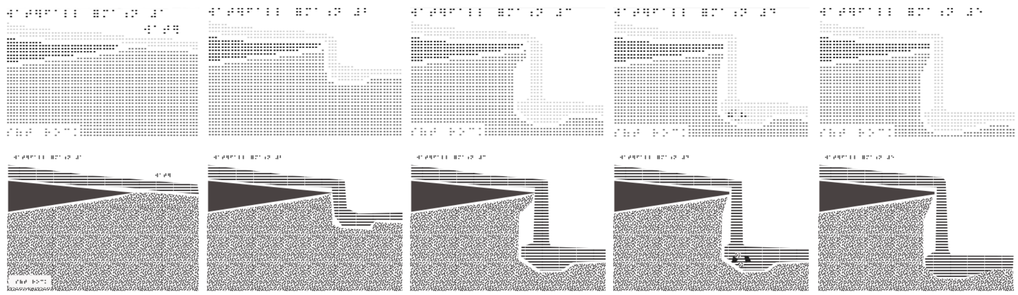

Figure 7: Five stages in the formation of a waterfall for presentation on a refreshable tactile display (top) and on swell paper (bottom)

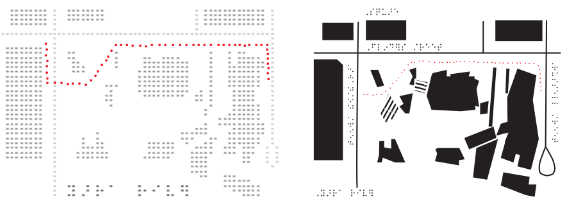

Figure 8: Map of Federation Square for presentation on a refreshable tactile display (left) and on swell paper (right)

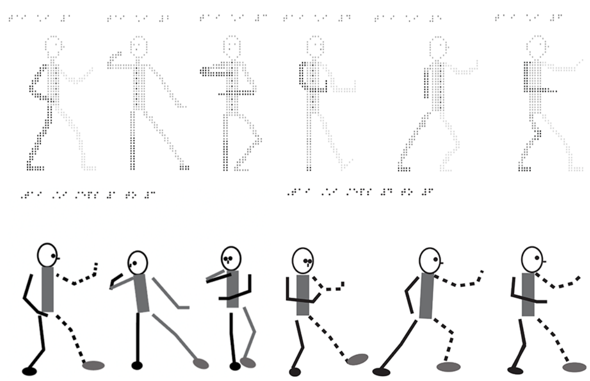

Figure 9: Sequence of six Tai Chi poses for presentation on a refreshable tactile display (top) and swell paper (bottom)

5.3 Method

Participants were shown all four tactile animations and the corresponding tactile graphics. The order of presentation was counterbalanced with participants split into four groups to adjust both the order of diagrams and the order of tactile graphic versus RTD.

The diagram description was delivered verbally so that other factors would not influence the results, such as braille reading ability, available space for braille labels, or different mechanisms for audio labels on the refreshable display compared with the tactile graphic.

The diagrams were shown one at a time until the touch reader was ready to go to the next. Once they had understood the static diagrams, the images on the refreshable display were run in sequence with a cycle speed between 2 and 8 seconds, as predetermined by Stephens. After viewing one cycle, the rate was adjusted until the touch reader was satisfied.

After the participant had seen each diagram (either as a tactile graphic or on the RTD), they were asked whether the static image was understandable and whether they could detect what changed. After they had seen both diagrams on a single topic, they were asked which was better in terms of initial understanding, detecting what had changed, getting a sense of motion, and which they preferred overall. They were also asked how the images might be improved, whether they had learned anything, and whether an RTD is useful for that type of diagram.

After the participant had explored all of the diagrams, they were asked a series of open-ended questions about their preferred animations and suggestions for future use. They were also asked eight questions from the System Usability Scale [20]. The term 'system' was replaced with 'refreshable tactile display' as the SUS tool has been found to be robust to such wording substitutions [8].

Sessions were conducted at the University or the participant's home and took around 90-120 minutes to complete. Video and audio recording was conducted. The audio was transcribed with additional notes regarding observed hand positions.

5.4 Results

Participant preferences for the RTD sequences compared with the tactile graphics are given in Table 2. Overall, there was a moderate preference for the tactile graphic for gaining an initial understanding of the static display (RTD=17; same=10; TG=21), whereas the RTD was preferred for detecting change (RTD=24; same=7; TG=17), giving a sense of direction and motion (RTD=20; same=13; TG=10) and overall (RTD=25; same=6; TG=17). However, there was a lot of nuance in these preferences and the findings differed for each diagram.

5.4.1 Representing Static Images on Refreshable Tactile Displays. Comparing the RTD with an equivalent tactile graphic for the presentation of static images, the most successful image was the Tai Chi moves, for which the static image was considered easier to understand (RTD=7, same =1, TG=4). This is because the use of pin heights was intuitive and aided in understanding of the body position (11 comments) much more than the use of solid and dashed lines on the tactile graphics (5 comments). Participant 1 said of the RTD diagram, "This has heights. It makes it more real." This finding was also reflected in responses to the map: "If you're thinking 3D,

Table 2: Preferred format for understanding the static image ('Understanding'), detecting the change from one image to the next ('Change'), giving a sense of direction and motion ('Movement') and preference overall ('Overall').

Preference	Refreshable Display	Same	Tactile Graphic	None
Understanding	**17**	**10**	**21**	**0**
Wave	3	3	6	0
Waterfall	3	3	6	0
Map	4	3	5	0
Tai Chi	7	1	4	0
Change	**24**	**7**	**17**	**0**
Wave	12	0	0	0
Waterfall	6	3	3	0
Map	0	2	10	0
Tai Chi	6	2	4	0
Movement	**20**	**13**	**10**	**5**
Wave	7	4	1	0
Waterfall	4	6	2	0
Map	3	3	5	1
Tai Chi	6	0	2	4
Overall	**25**	**6**	**17**	**0**
Wave	8	1	3	0
Waterfall	6	1	5	0
Map	5	3	4	0
Tai Chi	6	1	5	0

the buildings are taller. It's more intuitive" [P5]. Thus, RTDs with variable heights may be particularly well suited to diagrams where height or distance is important.

The Tai Chi graphics were also more successful on the RTD because the larger size enabled a clearer distinction of the nose and eyes (4 comments). While this size difference is due to a design decision made by the researchers, we believe it reflects real-world practicalities – space is conserved on expensive swell paper whereas there is no cost per page for display on an RTD.

By contrast, the static RTD was considered less successful than the tactile diagrams for both the wave and waterfall diagrams (RTD=3, same = 3, TG = 6). The tactile graphics were preferred because the areas on the diagram were considered more distinct (21 comments) and intuitive (8 comments). The use of a smooth surface to represent water and sandpaper to represent sand on the collage wave diagram was praised for being tactually distinct and meaningful. "This [water] feels gorgeous. This [sandpaper] represents sand well" [P2]. Additionally, the colour contrast on the tactile graphics assisted people with low vision. The RTD provided less contrast, particularly the separation of hard rock (level 4) and soft rock (level 3) on the waterfall diagram. Participant 9 suggested using a pattern such as every second dot to represent the soft rock, and two other touch readers agreed that this provided a much better tactual contrast. It is clear that a greater effort must be made in the design of RTDs to ensure that there is adequate distinction between different regions of the graphic.

Table 3: Average desired frame rate on the Graphiti display (secs), and number of participants (n=12) who learned something new from viewing the graphics (in either format) and thought that RTDs are useful for this type of graphic.

Graphic	Frame rate	Learned	RTD useful?
Wave	2.25	10	11
Waterfall	7.17	10	10
Map	n/a	9	11
Tai Chi	9.18	6	11

5.4.2 Representing Sequences and Moving Images on Refreshable Tactile Displays. The materials for this study were chosen specifically to examine the representation of change and movement, where change was defined as being able to detect what had changed from one image to the next. The RTD was rated as somewhat better in conveying change (RTD=24, same =7, TG=17).

Movement was defined as giving a sense of the moving object's direction and motion. Again, the RTD performed better than tactile graphics for conveying movement (RTD=20, same=13, TG=10). The wave diagram was the most successful in terms of giving a sense of movement and animation (RTD=7, same=4, TG=1).

> "Now this is the power of the Graphiti, because you can feel it coming, it's like looking at a motion picture." [P5]

This success may be attributed to the simplicity of the diagram with changes localised to a small area and minor changes from one diagram to the next, allowing the sequence to be shown quickly, with an average preferred speed of 2.25 seconds per frame. Unlike the formation of a waterfall, waves moving towards the beach was a sequence that could be viewed almost in real time.

The waterfall was also successful in terms of giving a sense of movement on the RTD, although there was only a slight preference over the tactile graphics for this purpose (RTD=4, same=6, TG=2). Because the areas of change were larger and slightly more complex, the waterfall was viewed at a slower frame rate of 7.1 seconds on average. The direction of refresh from top to bottom matched the movement of the water and rocks from the top of the waterfall down to the plunge pool, which added to the sense of animation (1 comment).

The Tai Chi movements were the least successful in terms of giving a sense of movement. Even though the RTD was preferred over the tactile graphic (RTD=6, same=0, TG=2), four participants said that neither format gave a sense of movement and they had not thought about the poses as being part of a sequence: "I didn't think they were connected. It didn't occur to me" [P5]. This problem may have been due to the complexity of the diagram, combined with the large changes from one diagram to the next: "I can't really follow what's going on here, there's too much going on as it changes" [P6]. The sequence was viewed on the RTD at a slow frame rate of 9.2 seconds on average. In response to suggestions from participants, we created two additional diagrams with intermediate poses to be viewed between the original diagrams on the RTD. The two participants who viewed these diagrams agreed that it helped to connect the poses and give a better sense of movement.

Movement was defined differently on the map, using a moving cursor on the RTD compared with a static route on the tactile graphic. There was no clear preference for one format over the other to give a sense of movement on the map (RTG=3, same=3, TG=5). The experience of following the cursor was enjoyed for being novel and interactive (5 comments): "I liked following the dot" [P2]; "it was fun" [P1]. However, it was sometimes difficult to find the cursor (10 comments) and following a static route was definitely easier (10 comments).

We asked participants whether the sound of pins refreshing helped them to interpret the diagrams or movement. Only two people agreed, stating that the sound helped them to locate the moving pins. A further five participants suggested that the sound of the pins refreshing served more as an indication that something was changing, "like the sound of a curtain when you switch between scenes in a play" [P9].

5.4.3 Hand Movements. Hand movements were central to the detection of change. Participants were asked about their hand movements and the researchers made independent observations. Seven of the twelve participants reported that they had adjusted their hand movements for accessing graphics on the RTD. When using the RTD they would hold their hands in the region where they expected the change to occur so that they could feel the change under their hands (10 mentions), however this process relied on memory of the first image. By contrast, the tactile graphic provided the opportunity for parallel comparisons by exploring two images simultaneously (4 mentions), with one hand on one image and the other hand on a second image that was placed either beside or underneath the the first.

The wave and waterfall were considered best for detecting changes on the RTD because the region of change was predictable and in a relatively small region. When following the cursor for the map route, participants would use the finger pads on both hands, lined up in the direction they expected the cursor to travel based on the verbal description. Detecting changes in the Tai Chi poses was much more difficult on the RTD because the arms and legs were so spread out that they could not all be felt at once (6 comments). Stephens reported that it was easier to use a large area of the hand to detect change on the RTD because the pins are so prominent. She tended to use the finger pads to focus on the detail of what is changing (for simple diagram) or the key area of interest (for more complex diagrams), combined with the flat of both hands to get an overview.

It was noted that the swell paper moved around while the participants were examining the diagrams; this was particularly problematic for a braille reader with use of only one hand. The RTD's weight was advantageous in this context as it was completely stable.

5.4.4 Practical Considerations. Beyond user experiences, practical considerations are also factors in the likely adoption and use of RTDs. When asked about the disadvantages of RTDs, participants mentioned the limited contrast between different areas (7 participants), the low resolution or wide spacing between the dots (n=5), the high cost (n=5), unreliability with the potential for individual dots to fail or for the whole device to break down (n=3), the weight (n=2), the hard feeling of tall dots on the fingers (n=2), and the slow refresh rate (n=1). While some of these issues may be overcome with advances in the technology, others are likely to remain as limitations inherent to the device. We did not ask explicitly about advantages of the RTD, but participants commented on the fact that each electronic diagram shown on an RTD has zero associated material costs, allowing for access to a greater number of images (5 comments). In terms of usability, the average SUS score was 79.9 (sd=6.2), which can be interpreted as 'good' [8]. However, this result is difficult to interpret as the participants were not operating the RTD themselves. Note also that scores were adjusted for the removal of questions 7 and 8 relating to the system integration and consistency, as several participants were unsure how to interpret or answer these questions. The SUS is robust for the removal of one question [46] but results with two questions removed should be interpreted with caution.

As researchers and accessible format producers, one of the biggest advantages of the RTD for us was the ability to quickly and easily change diagrams while discussing them with the touch reader. For example, we were able to move lines further away from each other on the map, test whether tactile distinction was easier or more difficult with a blank line of separation between areas, and trial different dot patterns. By contrast, it was much more difficult for us to go back to the office to edit and re-print the tactile graphics. Four of the participants likewise commented on the value of quick editing on the RTD: "one of the strengths of refreshable displays is the ability to refresh and show what is needed at the time rather than predetermined" [P4]. This immediacy is of particular value for the blind and low vision community to cater for individualised needs, as there is wide diversity in terms of eye conditions, co-occurrence with other disabilities, and user skills and experience with tactile graphics. RTDs therefore address the difficulty of modifying traditional tactile graphics, which has been identified as problematic in prior work [2, 49, 64, 73].

5.4.5 Potential Application Areas for Refreshable Tactile Displays. Participants in the user study reported learning about the subject matter from viewing the images presented as tactile graphics and on the RTD. As shown in Table 3, the majority of participants agreed that they had learned something about the subject matter from all of the diagrams except Tai Chi, for which only half agreed. Often, what they learned was basic concepts such as the shape of a wave, the structure of a waterfall, and an overview of an area that they had visited but not understood as a whole. For example, "I had sort of imagined a waterfall as a perfectly smooth curve whereas in reality it wouldn't be because of the rocks underneath it" [P8].

As a novel device able to give the first access to tactile animations without input from the user, it is not surprising that the RTD was found to be engaging (15 comments): "I get very excited when there are toys to play with" [P2]. This could help with student engagement and therefore learning in the classroom, particularly as it provides a tangible means for exploring visual narratives [74]. As one participant commented, "I could sit here for ages watching it. So cool" [P6].

When asked what applications they might have for animated tactile graphics in their life, all but one participant was able to give examples. These included maps (n=5); for collaborating with charts and process diagrams at work (n=3); for fun applications such as following live sports (n=2), learning dance steps or exercise moves (n=2), playing games (n=1), watching demonstration videos (n=2) or watching the weather radar (n=1); and for concept development such as learning about print notation (n=3), visual communication such as hand gestures and body language (n=2) and traffic movement for orientation and mobility (n=1). While only one of the participants was a current student, many of them also suggested that RTDs would be especially useful for students to gain access to educational materials (n=7).

6 DISCUSSION

6.1 Potential of Tactile Animations on Refreshable Tactile Displays

Feedback from participants in our studies makes it clear that there is a high level of enthusiasm for access to tactile animations. RTDs can be used to show change over time and for some images they hold advantages over traditional tactile graphics for conveying movement, depth and height. However, this was not true for all images and there were trade-offs in terms of resolution and textural properties.

In the best case, the changes to the image were localised and allowed the touch reader to feel the changes under their hand. The wave and waterfall were favoured on the RTD because touch readers knew where to look for the changes, which they could then follow as animations. Conversely, the Tai Chi diagram was the most difficult to follow because it was not possible to follow the changes to the four limbs at the same time.

6.2 Design Considerations for Animated Graphics Shown on Refreshable Tactile Displays

The process of creating, using and sharing graphics on an RTD provided insights into design considerations that are either specific to RTDs or more important when using this format.

- **Simplify:** As the images need to be read quickly and on a low-fidelity screen, moving tactile images should be very simple, with less detail than on an equivalent tactile graphic and much less detail than the original print graphic. This aligns with O'Modhrain's guidelines for tactile graphics on refreshable displays [55].
- Use **height** to distinguish different components within the diagram. Specifically, pin height can signify the height of objects seen from above, or to signify distance by representing closer elements with higher pins. Pin heights of 0.5mm, 1mm and 2mm were clearly distinguishable from one another.
- **Texture patterns**, such as stripes or alternative pins in a grid, can also be used to clearly distinguish large areas on the diagram.
- Use **blinking** pins to direct attention to important areas of the graphic. This recommendation is in line with prior work with RTDs and travel route planning [34].
- Ideally, **movement should be restricted to one region** of the diagram, especially since simultaneous movement in multiple regions can be difficult to follow by touch.
- The ideal **display duration** depends on the complexity of the diagram and the amount of movement between frames – more complex diagrams require longer display times, and less change between sequential diagrams allows faster display times.
- If the display refreshes one line at a time, **consider the direction of the refresh** when designing sequences of moving images. Movement in the opposite direction to the refresh can be difficult to interpret.
- Make use of the ability to **edit images while they are being used**. This study benefited from the ability to immediately adjust diagrams based on feedback from touch readers, either to improve the diagram or to cater to individual needs and preferences. On-the-spot editing could also be used to gradually add features (or remove braille labels) as the learner's understanding advances. Such an approach has been proposed as best practice [12] but implementation is difficult using traditional tactile graphics.

6.3 Considerations for Refreshable Tactile Display Technology

Our study reinforces that a limitation of current RTDs is their **low resolution**. Even with 2,400 pins, less detail could be conveyed on the Graphiti display compared with an equivalent sized tactile graphic. Moreover, the wide spacing between pins meant that it was difficult to accurately perceive areas across the display simultaneously. These findings align with a previous study in which shape recognition on RTDs was found to improve when the pin spacing is decreased and pin array size is increased [27].

Labels and accompanying descriptions are always important to support understanding of tactile images due to the bottom-up nature of tactile image consumption [32, 50]. As there is less space available for braille on RTDs compared with tactile graphics, other strategies should be built into the devices, such as touch-triggered audio labels or an accompanying braille display.

Use of **high contrast or colour** is of great value to touch readers who have some residual vision. White pins against a black background did not provide sufficient contrast because it was difficult to see whether they were raised. Designers of future devices should consider further measures to provide visual cues, such as the coloured lights on the TouchPad Pro.

6.4 Limitations and Future Work

During our study, we wanted participants to focus on exploring the tactile animations frame by frame in order to gather rich and detailed feedback. Consequently, we did not ask participants to operate the RTD themselves or independently access the description of the graphic. When these tasks are added in an individual home setting, touch readers may lose their place in the graphic. A key question is how best to support independent interaction while maintaining relative positioning of the hands and fingers. Future usability studies are required to better understand ease of use in real-world settings.

Another avenue of potential research lies in the drawing and collaboration capabilities of RTDs. This was of interest to several of our participants. Although there is prior work in this area [3, 38, 39, 53], the use of touch sensitive RTDs with larger tactile surfaces, audio feedback, and network capabilities offers new possibilities and warrants further research.

Lastly, design guidelines for tactile graphics are an integral tool for the transcription process. Even in our brief study, we have already identified a number of ways graphics need to be designed differently for use on an RTD. These guidelines need to be expanded for a wider range of diagrams and users.

6.5 Conclusion

Given the considerable cost of refreshable tactile displays, independent studies like this provide important information to help potential consumers decide whether an RTD is a worthwhile investment. To our knowledge, this is the first study that has sought to gain understanding of the most suitable use cases and efficacy of RTDs for tactile animations.

Our results suggest that RTDs have considerable potential for use in education, orientation and mobility training, and collaboration in the workplace. While their use for entertainment was of some interest, support for education was seen as much more important. Unsurprisingly, RTDs demonstrated a particular strength for conveying motion, however some previously unconsidered benefits also emerged, such as allowing for on-the-spot editing and customisation for individualised needs. Further work is needed to obtain a nuanced understanding of what diagrams are most suited to the RTD.

This work provided the basis for a series of preliminary guidelines and design considerations relating to both the graphics being presented on RTDs and also the design of RTD technology. We hope that these can be adopted to further explore development of this important technology as well as determine best practice for portraying graphic material on these RTDs.

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A VERBALISED DESCRIPTIONS OF SAMPLE GRAPHICS

These descriptions were provided verbally to accompany the sample graphics as they were explored tactually by touch readers in the Evaluation phase. Pauses were inserted while the graphic was being explored, and additional guidance was given if needed to ensure that the key features had been identified.

A.1 Wave

Collage: This diagram shows how waves form as they come in towards the beach. The diagram is a cross section showing the water (raised smooth area) and sand (sandpaper on the lower right).

RTD: This is the first of seven diagrams showing a wave as it forms and comes in towards the beach. The diagram is a cross section showing the water (highest dots) and sand (lower dots on the lower right, in a low triangular shape).

Both formats: The wind is blowing from the ocean (left) to the beach (right). Starting from the left, the first waves are beginning to form as low lumps. The air pressure creates the waves, with upper layer of air sink on either side of the wave. The wave gets higher as the sea floor gets higher. Friction from the beach slows the lower part of the wave but the upper part continues to move forward, forming a curve. After the wave breaks, swash moves up the beach and backwash moves down.

A.2 Waterfall

Both formats: This is the first of five diagrams showing the creation of a waterfall over time.

Swell paper: The diagram shows a cross section of the earth, with water at the top (horizontal stripes). The water is flowing down from left to right. There is a triangle of hard rock on the left, just below the water. It is shown as solid fill. Below the hard rock there is a large area of soft rock, shown with textured fill.

RTD: The diagram shows a cross section of the earth, with water at the top (low dots). The water is flowing down from left to right. There is a triangle of hard rock on the left, just below the water. It is shown with high dots. Below the hard rock there is a large area of soft rock, shown with slightly lower dots.

Both formats: Waterfalls are often formed where a layer of harder rock overlays a layer of softer rock. Diagram 2: As the river passes over the softer rock, it is able to erode it at a faster rate, forming a step in the river bed. The water is lower on the right now, where the soft rock has eroded. Diagram 3: Erosion continues, and cuts underneath the hard rock. Diagram 4: The tip of the harder rock has collapsed and fallen into the plunge pool, because there was not enough support underneath it. Diagram 5: The rocks and boulders under the plunge pool and the hydraulic action have further eroded the plunge pool and notch.

A.3 Map

Note that all participants were familiar with the area depicted on the map, but did not know all of the buildings.

Both formats: This is a map of Federation Square, seen from above.

Swell paper: Roads are shown as solid lines. Buildings are shown as filled shapes. Stairs are shown as striped blocks. A walking route is shown with a dotted spur wheel line.

RTD: Roads are shown as low lines. Buildings are shown as taller blocks. The position I am describing will be indicated by a blinking pin.

Both formats: Flinders street runs along the top of the map, Swanston street is to the left, Russel street is on the right, and the Yarra River at the bottom.

Young and Jackson's pub is at the top left corner. This is where the famous painting, Chloe, hangs. Moving right across Swanston street, we find St Paul's Cathedral. Further along Flinders street we come to Hosier Lane, famous for its street art. After Hosier Lane is the Forum Theatre. Moving down across Flinders street, there is NGV Australia. Below the NGV is ZINC, a venue for events like weddings. Moving left from ZINC we come to BMW Edge, a multi-purpose theatre that is open to the atrium (the space to the left of the NGV). Moving left from the atrium we come to ACMI, the Australian Centre for the moving image. On the corner is the Melbourne Visitor Centre, which is currently undergoing construction to form an entrance to the new Town Hall underground train station. Crossing over Swanston street, we come to Flinders street station. In the bottom left corner, there is the Transport Hotel.

When you are ready, let's trace the route on the map. The route goes from Flinders Street Station to the replacement buses for the Frankston, Pakenham and Cranbourne lines. Let's start at the corner steps of Flinders street station. First we head to the pedestrian crossing at the tram stop on Swanston street. We cross the road from Flinders street station to Federation square. The Information centre is on our left. We follow around the information centre to the footpath on Flinders street. We pass by ACMI and the atrium on our right. We turn right when we reach Russell street. The bus stop is behind NGV Australia.

A.4 Tai Chi

Both formats: This series of three diagrams shows a sequence of movements for Tai Chi. There are three figures per page, progressing from left to right. Each figure has a rectangular body with arms, legs, feet, and a head with eyes and a nose. There may be one or two eyes, depending on the angle of the head. There is a dotted line on the body, representing shirt buttons down the centre front of the body.

Swell paper: Solid lines for the arms and legs indicate that they are positioned in front of the body. Dotted lines for the arms and legs indicate that they are positioned behind the body.

RTD: The body in the centre is at height 2. Lower pins indicate that the arms or legs are further away than the body. Higher pins indicate that the arms of legs are closer than the body.

B EVALUATION PARTICIPANT PROFILES

Table 4: Profiles for participants in the evaluation study, giving their age range, level of blindness (totally blind or legally blind), onset of vision impairment, and self-rated level of competency using tactile graphics.

ID	age	blindness	onset	TG competency
1	40s	total	acquired	proficient
2	40s	legal	acquired	beginner
3	50s	total	congenital	beginner
4	50s	total	congenital	expert
5	50s	legal	congenital	beginner
6	20s	legal	acquired	proficient
7	20s	legal	acquired	expert
8	60s	total	congenital	expert
9	60s	total	congenital	proficient
10	30s	legal	acquired	proficient
11	40s	total	congenital	proficient
12	50s	legal	acquired	beginner