Feeling Fireworks: An Inclusive Tactile Firework Display

Dorothea Reusser
Disney Research and ETH Zurich
dorothea.reusser@gmail.com

Espen Knoop
Disney Research
espen.knoop@disneyresearch.com

Roland Siegwart
ETH Zurich
rsiegwart@ethz.ch

Paul Beardsley
Disney Research
paulbear@inf.ethz.ch

ABSTRACT

This paper presents a novel design for a large-scale interactive tactile display. Fast dynamic tactile effects are created at high spatial resolution on a flexible screen, using directable nozzles that spray water jets onto the rear of the screen. The screen further has back-projected visual content and touch interaction. The technology is demonstrated in Feeling Fireworks, a tactile firework show. The goal is to make fireworks more inclusive for the Blind and Low-Vision (BLV) community.

A BLV focus group provided input during the development process, and a user study with BLV users showed that Feeling Fireworks is an enjoyable and meaningful experience. A user study with sighted users showed that users could accurately label the correspondence between the designed tactile firework effects and corresponding visual fireworks. Beyond the Feeling Fireworks application, this is a novel approach for scalable tactile displays with potential for broader use.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; *Haptic devices*; • **Hardware** → *Haptic devices*;

KEYWORDS

Accessibility; Large Interactive Screen; Haptic Device

ACM ISBN 978-1-4503-5970-2/19/05.
https://doi.org/10.1145/3290605.3300659

ACM Reference Format:
Dorothea Reusser, Espen Knoop, Roland Siegwart, and Paul Beardsley. 2019. Feeling Fireworks: An Inclusive Tactile Firework Display. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland, UK*. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3290605.3300659

1 INTRODUCTION

Fireworks are a visual experience enjoyed throughout the world, being used to mark special events of the year and also as central feature in the night-time entertainment of the Disney theme parks. To provide more inclusivity for Blind and Low-Vision (BLV) users, we have made a large-scale tactile display to render tactile fireworks that are analogous to visual firework effects in the sky. Inclusive and assistive technology often has a functional goal, but this work differs in its aesthetic intent. We envisage it as an installation at a firework show in which the tactile effects and visual fireworks are synchronised, in order to attract all crowd members, both BLV and sighted, in a shared experience of *Feeling Fireworks*.

Tactile fireworks are an interesting and challenging scenario to study from a haptic interaction design viewpoint, and a stepping stone towards broader applications. For a cross-modal firework experience, the tactile effects should convey a similar experience to the fireworks in the sky. This is not possible with existing haptic screens, and our work is an attack on the problem.

To create an analogous experience to visual fireworks, tactile fireworks should be dynamic and fast-moving, and extend spatially across the screen. However, most existing systems for tactile stimulation present content which is either (a) temporally static or (b) at a single location. Temporally-static content—e.g. tactile relief maps [46]—is analogous to a static visual image, and affords interactions using *active touch* where users move their hands and explore the tactile content. In contrast, single-location content with temporal dynamics (vibrotactile stimulation)—e.g., the Haptuator [45], smartphones, and wearable devices—is more analogous to audio, and lends itself to *passive touch* interactions where

Figure 1: Feeling Fireworks is a large-scale tactile display which generates a tactile firework show, providing an extra dimension for Blind and Low-Vision (BLV) users, in the context of an enjoyable experience that can be shared by BLV and sighted users.

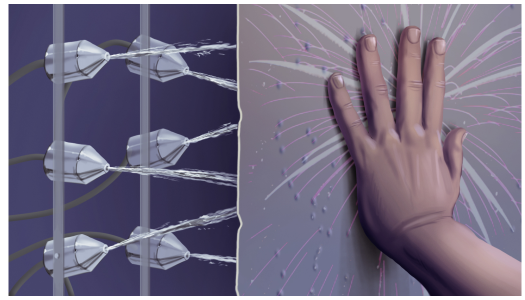

Figure 2: A set of pan-tilt nozzles direct water jets at the rear surface of a flexible screen, to generate tactile effects on the front surface.

the user is static and perceives the tactile content. The tactile firework experience combines the spatial and temporal dimensions and can be considered analogous to *tactile video*, supporting both active and passive touch interaction.

Feeling Fireworks was informed by working with a BLV focus group, including representatives from a national BLV association, throughout the development process. A user study with BLV users demonstrates that the BLV community perceive the system as an enjoyable and meaningful firework experience, while a user study with sighted users demonstrated that the tactile effects meaningfully represent their corresponding visual effects.

The system consists of a vertical tactile screen of size 90×90 cm, as shown in Fig. 1. The concept is that the view of the sky in a firework show is mapped to screen space—for example rockets launch from the base of the screen and explode at the screen center. Tactile effects are achieved using a novel approach in which water jets are sprayed onto the rear of the flexible screen and a user senses the impact on the front surface, as illustrated in Fig. 2. The water nozzles are mounted on pan-tilt units in order to render tactile motion, including fireworks that move smoothly across the screen, without a need for a large number of actuators. Different nozzles are used to create different sensations. Feeling Fireworks utilises back-projection on the tactile screen to show visual fireworks, and to show a GUI that is activated by screen finger presses, for use by low-vision and sighted users.

Motivation. This work was originally motivated by the idea that one could improve accessibility for BLV users at a firework show. This led to the technical concept of a flexible screen with rear placement of water jets to provide a large tactile field at achievable cost. Early stage discussions with a BLV Focus Group then led to key usability features, such as the use of rear-projection for low vision users, and tactile home points for BLV users.

Contributions. This paper presents a novel approach for a large haptic screen with the following properties: dynamic, high-resolution, scalable and cost-effective. This includes a novel nozzle design for a radially-expanding spray as a valuable tactile effect. The user studies demonstrate that the tactile fireworks are effective, being meaningful analogs of visual fireworks and providing an enjoyable experience for all. Finally, there is a contribution in our investigation of tactile video, along with active-touch and passive-touch modes of interaction, with value for other areas of haptic interaction design.

2 RELATED WORK

The application requirements are a tactile screen with effects that are sufficiently dynamic and high spatial resolution to represent visual fireworks. To enable a shared experience, the screen should be cost-effectively scalable to one or more users. Related technologies like inFORM [11] and TableHop [39] are not applicable to this problem because they do not scale with high spatial resolution in a cost-effective way. TeslaTouch [3] has been studied for low-vision users [56]—however it may not provide sufficient spatial resolution and tactile gamut for compelling firework effects and cannot be explored with two hands. The Tactile Brush [24] and ultrasound haptics [35] are not suited to our screen-based interaction.

Tactile fireworks

Fireworks are an aesthetic and entertaining experience, and their tactile representation is not confined to conveying information but relates to the area of affective haptic stimulation [31, 48]. Directly related to our goal at least in spirit, although not approach, is the work of VocalEye [10] in which a sighted person hand-draws tactile fireworks on a blind person's back.

Haptic technology for BLV users

Rendering text: The Optacon [15] is an early example of a technology that used a camera to capture text, and an array of piezoelectric actuators to render it. Refreshable Braille displays [22] represent current technology for symbolically rendering text, although with relatively low adoption rates in the BLV community.

Rendering static graphical content: Work on static tactile surfaces includes tactile graphics [18] and tactile maps [16, 46]. Static tactile surfaces are augmented with a computer vision system in the work of Shi et al. [41] to determine the current focus of interest of the user and thereby activate supplementary audio information.

Rendering dynamic graphical content: A number of refreshable Braille displays have been developed, that feature an array with a large number of actuated pins that can be used both to render Braille text and also to reproduce graphical content [5, 7, 17, 23, 57]. The BrailleDis [51] combines an actuated pin display with multitouch input for interactivity. Recently, Bornschein et al. [4] combined a BrailleDis refreshable Braille display with four different input methods including gesture-based input and freehand drawing, to create a tool that allows BLV users to efficiently create appealing images. However, for large screens with high spatial resolution these technologies would require a very large number of pins, causing high complexity and cost.

LineSpace [44] is a screen on which lines of plastic are interactively extruded on the surface to provide information requested by a user. The system can also remove lines, allowing for the drawing to be refreshed. Kim et al. [28] present tactile 'movable pictures' which provide children a way to manually explore and change the state of a modular object to understand concepts like up and down. Twyman et al. [50] describe the augmentation of wearable technology, such as smartwatches, with haptic content using a T-PaD.

Methods for tactile stimulation

The problem of presenting users with haptic content as they explore and interact with a device has been tackled in a number of different ways. With the advent of touch screens, much work has studied how these can be augmented with tactile content. Harrison et al. [21] present a touchscreen with buttons that can be raised from the surface of the screen as required, using pneumatic actuation. Devices have also been created that can produce arbitrary tactile content: the T-PaD [55] modulates the friction between a touchscreen and the user's finger, and Rekik et al. [38] use ultrasonic vibrations to produce vibrotactile feedback on a touchscreen based on the finger location. The BubbleWrap [2] instead uses an array of vibrotactile actuators below the screen.

Another approach to creating haptic screens is to use an array of actuated pins that can be moved to approximate adaptive and dynamic surfaces. Examples of this approach include large-scale shape displays [11, 12, 20, 25] and also smaller-scale displays with braille-like dots and faster update rates [27, 33, 57]. However, the number of actuated pins quickly becomes very large for large displays or high spatial resolution, and the cost and complexity grows accordingly.

Novel actuation methods for haptic stimulation have also been explored, including ultrasound [6], magnets [49], jamming [13], electroactive polymers [30], shape-memory alloys [31], magnetorheological fluids [26] and also electrical sparks [43]. Such novel actuators could allow for large-scale low-cost screens, but further research in this area is required.

Haptic feedback can also be generated using wearable devices, allowing users to move freely in space. Pacchierotti et al. [37] present a recent review. This can enable users to interact with virtual objects [40]. For our purposes, however, we were interested in the affordance offered by a large-scale tactile screen.

Shuai et al. [42] use water jets for tactile stimulation, with 6 fixed small water jets that are directed at a static fingertip. They use hot and cold water to create different sensations, and report that the resulting sensations are 'natural and comfortable'. However, the approach taken by Shuai does not readily scale up to large screens as a large number of jets and valves would be required.

3 SYSTEM DESIGN

The system is housed in an upright frame with the exception of the controlling laptop which sits outside, and it runs off a single power cord. See Fig. 3. The flexible screen is backed by five pan-tilt nozzles that deliver water jets, with different nozzles to generate different tactile effects on the screen surface. A projector is used to back-project visual content on the screen, and the screen is also interactive, using a Kinect to detect screen finger presses.

Frame and screen: The frame is built from modular aluminium profiles for portability and assembly/disassembly. The screen is 90×90 cm and is made from chlorinated latex (the same material as medical gloves) attached tautly to the frame. Different sheet thicknesses were investigated—thicker sheets are

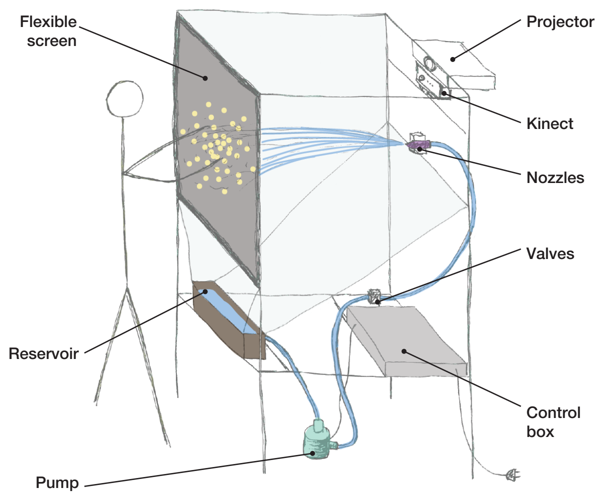

Figure 3: Schematic of the system. For clarity, only one nozzle is shown.

more robust but attenuate high-frequency tactile content—and a 0.35 mm thickness was chosen as a suitable trade-off between robustness and attenuation. A thin layer of silicone oil is applied to the front of the screen for smooth feel.

Tactile home points: To aid user orientation, the screen has a raised design located at bottom center, and a raised ellipse at the screen center. The lower home point defines the start point for fireworks that are firing upwards, and the ellipse provides guidance for tactile effects in the sky.

Pan-tilt nozzles: There are five nozzles, three for rockets, one for an expanding flower effect, and one for a crackling cloud effect. Each nozzle is mounted on a pan-tilt unit driven by two standard servo motors. Silicone rubber boots are used to protect the servo motors from water spray. Inverse kinematics between the pan-tilt unit and the targeted screen position is done with a look-up table, obtained in a manual calibration procedure. Calibration is a one-time operation, and re-calibration does not need to be done after disassembly/reassembly. The calibration maps nozzle pan and tilt to screen location, and is done on a per-nozzle basis, so this accounts for effects of gravity on the water jet.

Closed water cycle: Water is pumped from an eight-litre reservoir at the base of the screen. The pump is a Levitronix BPS-600, chosen because it is a near-silent medical product. The water strikes the screen and falls into the reservoir for re-use. Each nozzle is controlled by a solenoid valve, allowing for individual nozzles to be turned on and off in any combination. The pump speed is variable which allows tuning for tactile effects with different pressures. The pump is not damaged when all nozzles are turned off and there is no flow—this enables sharp off-on transitions for, e.g., tactile explosions, by leaving the pump running and using the valves for switching.

Electronics and control: The system is controlled by a laptop plus Arduino Mega. The laptop is (a) connected to the Arduino, (b) controls the projector and backprojected content, and (c) controls the Kinect plus interaction with screen finger presses. The Arduino controls the pump, the nozzle valves, and the pan-tilt of the nozzles. The projector and Kinect are elevated and shielded from water contact. All remaining electronics apart from the laptop are in a waterproof box. The projector is a wide-angle Mitsubishi WD500U-ST. Animated fireworks for projection are generated using FWSim [14]. A Kinect at the rear of the screen is used to detect screen finger presses as described in Kingsley et al. [29], to select between different firework effects. Individual fireworks can be selected via a projected GUI on the screen, or by a physical button box with Braille and text labels and 5 large buttons, suitable for use by BLV users. The Kinect requires the user to press ~5 cm into the screen. Both using the button box and the GUI, there is a delay of 2 s before the start of the firework, allowing the user to position their hands on the screen.

4 NOZZLE DESIGN

The key design elements available for creating varied tactile effects are:

- Custom nozzles and/or spray patterns
- Use of pan-tilt nozzles to position and move tactile effects on the screen
- Use of pan-tilt to impart a high-frequency jitter to a nozzle, to produce high-frequency droplets on the screen
- A novel nozzle design in which a nozzle membrane deforms under varying pressure, allowing spray pattern to be controlled by pump pressure—this was used to produce a dynamic radially-expanding spray pattern

The remainder of this section describes how these elements are used in the design of three tactile fireworks, shown in Fig. 4.

Rocket effect

The tactile effect for a rocket is produced using a standard nozzle that generates a single jet as shown in Fig. 4-top. A non-laminar nozzle is used in preference to a laminar one because it generates more high-frequency content on the screen, to which human touch is highly sensitive [34]. Pressure is increased for a short duration (0.5 s) to create an explosion at the rocket's apex. Three nozzles are used simultaneously to represent multiple ascending rockets.

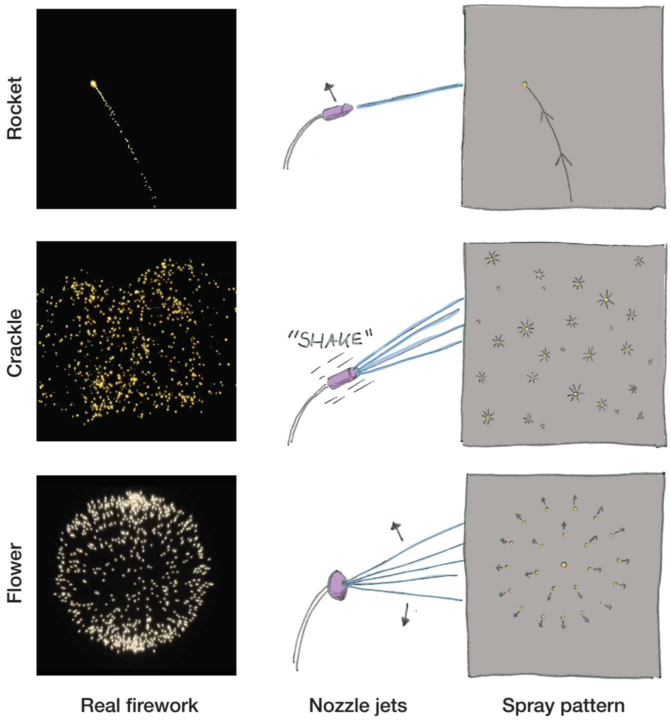

Figure 4: Illustration for three different tactile effects for fireworks. At left, image of the visual firework; at center, schematic of the corresponding nozzle; at right, the spray pattern.

Crackle effect

A crackle firework is a cloud of light flashes accompanied by a crackling sound. The tactile effect is produced using a nozzle that generates 17 narrow water jets as shown in Fig. 4-middle. The pan-tilt unit jitters the nozzle, creating many small drops on impact with the screen, to generate a tactile and spatially-distributed equivalent to visual crackle.

Flower effect

A flower firework is an explosion into a radially-expanding bloom of points of light as shown in Fig. 4-bottom. A first intuition for creating this effect might be to use multiple nozzles, but that clearly becomes prohibitive in the number of nozzles. Instead, our novel design is based on a silicone membrane with a set of apertures at its center, as shown in Fig. 5. Under increasing water pressure the membrane bulges and this causes a radial divergence of the apertures and water jets, with the corresponding radial tactile effect on the screen. Thus, a dynamic and controllable spray pattern is achieved using a single nozzle with pressure variation, without the need for additional actuators.

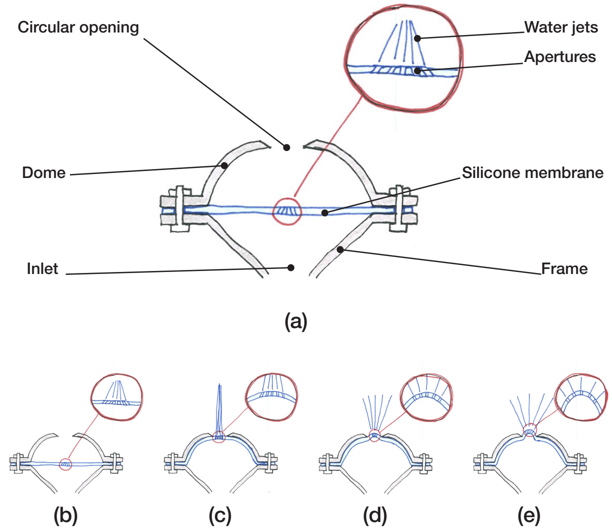

Figure 5: Flower firework nozzle. (a): annotated schematic cross-sectional view of nozzle. (b-e): sequence showing the deformation of the silicone membrane. (b): silicone membrane is flat in rest configuration. (c): at p_c, the membrane comes into contact with the dome. (d-e): further increasing the pressure causes the membrane to bulge through the circular opening and the water jets to diverge.

The approach is shown in detail in Fig. 5. A silicone membrane is enclosed by a rigid dome with a circular opening. There are three phases in use:

- Below a critical water pressure p_c, the silicone membrane is not yet in contact with the dome. The curvature of the membrane is low. The apertures in the silicone membrane are angled inwards towards the centre axis of the nozzle as shown in Fig. 5b so that the water jets converge—this has the effect of generating a single jet which passes through the dome's circular opening.
- At p_c, the membrane is in contact with the dome. The curvature of the membrane surface is still small at p_c, and the individual water jets are still generating a single jet.
- Above p_c, the membrane is pushed into the dome's circular opening—the surface curvature increases rapidly and the apertures in the membrane, hence also the water jets, diverge radially.

The rigid parts of the nozzle are 3D-printed, and the silicone membrane is moulded using DragonSkin 30 silicone (Smooth-On, Inc). The behaviour of the membrane was tuned by varying the following parameters: membrane thickness, aperture size and spacing, and convergence of apertures. Best values were found empirically, as follows: membrane thickness of 2.0 mm with 18 apertures of diameter 0.4 mm, spacing 0.8 mm, angled such that the beams at rest converge to a point 20 mm above the membrane surface.

Specification of the tactile effects

Here we report the size of the different effects on the screen, as well as the delay between switching the valve and the effect being felt on the screen.

- Rocket: 6 mm diameter; 100 ms switching time
- Flower: 20-600 mm diameter (continuously variable); 400 ms switching time
- Crackle: 400 mm diameter; 100 ms switching time

The resolution of the pan-tilt nozzles in screen space is 5.5 mm, which is similar to the size of the rocket firework. In our implementation, we consider predefined firework sequences. Hence, the nozzle switching times can be compensated for. For all the effects, the maximum velocity of the water jet on the screen is 4.7 m/s. The nozzles produce audible drumming sounds on the screen, which we found to add to the firework experience. However, additional audio effects could also be added if required.

5 USER EVALUATIONS

Three types of evaluation were carried out: a focus group was formed early in the project to obtain timely input from the BLV community; a user study was carried out on the final prototype with BLV users to assess the experience; and a user study was carried out on the final prototype with sighted users to assess how well the tactile fireworks represent visual effects.

Focus group with BLV users

A focus group was formed with three members of the BLV community including representatives from a national BLV association (two participants blind, one participant low-vision, all males aged 30–50). Two multi-hour sessions were held: an initial session with the first working version of the system, and a second session with the finished version.

In the first session, participants were presented with the concept of Feeling Fireworks and allowed to interact with the device and experience some basic tactile effects. This was followed by an open discussion session in which the group provided feedback and comments about the device plus general comments about accessibility technology.

Key non-technical discussion points included the following. *Aesthetic experience:* Many interesting developments are happening in functional technology for the BLV community [1, 8, 53, 54] but the idea of making a novel aesthetic experience is less common and was viewed positively. *Inclusivity:* The focus group were explicit that an inclusive experience should be something that is shared by all society, rather than a separated experience for a specific group. This marks a positive aspect of Feeling Fireworks which is designed for all users, both BLV and sighted.

Specific points were raised during the discussion that led to design changes for Feeling Fireworks. With the initial prototype, spatially local and fast-moving effects were sometimes difficult to localize. Once localized, however, participants did not have problems following rockets across the screen. This led to the incorporation of a tactile home point on the screen, to guide the users hands to the firework effects. The feedback of the first focus group session was also incorporated in defining parameters for different fireworks such as speed, duration and nozzle size.

One item that arose during the discussions is the role of prior knowledge when interacting with Feeling Fireworks. We expect this to be of particular importance in the absence of vision. On the one hand, if a user has detailed prior knowledge about the different tactile fireworks and what they represent then they would be expected to show increased performance with regards to identifying different firework effects and following a complex firework show. On the other hand, the elements of exploration and discovery which arise from interactions with a display that the user has little prior knowledge of could contribute to the enjoyment of the overall experience. It became clear that this is something which designers should be aware of if a device such as Feeling Fireworks was to be deployed in a public space.

A distinction arose between two types of interaction. In *global full-screen mode*, tactile fireworks are presented on a large area of the screen, requiring *active-touch* interaction by the user. For *local center-screen mode*, the user's hands are placed statically at a central position and the tactile effects are confined to that area, for a *passive-touch* interaction. There was no clear preference of one interaction modality over the other, but participants noted a clear difference in the perceived experience. Global effects were perceived as a more active and exploratory experience, whereas local effects were perceived as more passive and possibly a closer analog to the passive experience of watching a firework show. Somewhat surprisingly, participants also described local effects as more fatiguing than global effects. It seems that placing the hands statically on a vertical surface is not a common pose, while the movements involved in the active exploration allows for different muscles to be used and is less fatiguing.

We also observed in the focus group that trying to combine effects from even a relatively modest number of nozzles causes the tactile effects to become noisy and difficult to follow. For example, participants sometimes found it difficult to follow rockets which were superimposed over crackling to create a compound effect. This is also supported by the results in the user study—see the next section and the results for the compound firework 7 in the confusion matrix.

A key finding from the focus group sessions was the importance of a shared and inclusive experience. Participants explained that communities with accessibility needs do not like to feel that they are being separated out from others for a distinct experience but would like to be part of a common experience. We take the implication of this to be that the tactile fireworks should be analogous to the visual fireworks in the sky, for a shared experience. We test this with a user study with sighted users, below.

User study with BLV users

A user study was carried out on the final prototype with 14 BLV users (age range 20–45, mean age 33, one third of users female). Users experienced Feeling Fireworks, trying the five tactile firework effects that had proved most successful during development (Table 1: 1, 2, 5, 9, 10). This user study was concerned with evaluating the perceived firework effects as well as the overall experience. The study was carried out outside a lab environment (exhibition space at a conference), thereby providing a more realistic interaction scenario for a firework show. Users were free to interact and discuss with the researchers before and after taking part in the study. The conference, ATIA 2018, is a general accesibility conference but with significant BLV presence. Attendees include accessibility service providers and educators, as well as a large amount of lay-people who use accessibility technology. Feedback was obtained from attendees across all these groups. After the interaction, participants completed a questionnaire consisting of 4 Likert-scale questions, and were also asked to comment on their overall experience of Feeling Fireworks. An optional question, which all users chose to answer, was whether the user was blind or low-vision from birth (in which case the user has no or reduced visual frame of reference for the experience) or from later in life (in which case there has been an earlier full experience of visual fireworks).

Results. Out of the 14 BLV participants, 2 reported they were blind from birth, 7 reported they were blind from later in life, 1 reported they were low-vision from birth and 4 reported they were low-vision from later in life.

The results from the questionnaire are summarized in Fig. 6. It can be seen that BLV users enjoyed the experience, with 40 % agreeing strongly with the statement 'I enjoyed interacting with the tactile firework display' and no users disagreeing with the statement. It can be seen that the tactile effects were generally easy to differentiate, and also that the experience did correspond to user expectations for a tactile representation of fireworks.

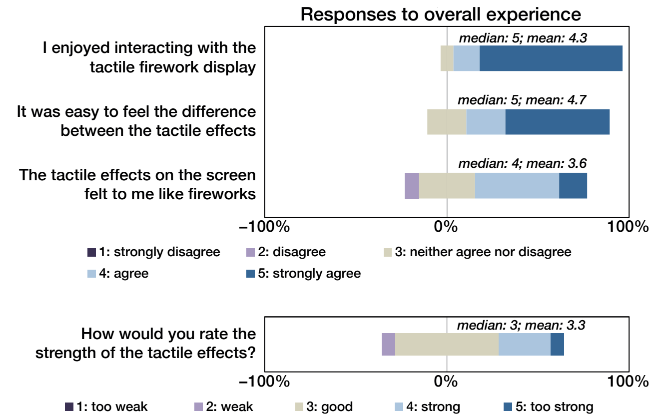

Figure 6: BLV user responses on final prototype.

Overall, participants' qualitative responses were very positive, with quotes including: "Potential is enormous. Fantastic approach.", "Unexpectedly good—a lot of people promise good haptics for BLV community but fall short. Feeling Fireworks lives up to its promise, it is precise, and has sound. it would be very cool to pair it with real firework sounds."

Comments from participants who were blind from birth include "First time to get the feeling of what's happening in the sky. Fountain—awesome, first time had a feeling of that is what is a fountain.", "My mom always told me about fireworks but now I understand it." and "Now I know why people like fireworks." Two participants who were blind from later in life independently suggested that this would be particularly valuable for users who are blind from birth and have never experienced fireworks.

Participants also provided constructive suggestions for the design of Feeling Fireworks. It was suggested to not use latex due to allergy reasons. Several participants suggested that the water temperature could be varied for different effects. Some participants found the upward motion of the rocket difficult to follow, and suggested it could be slowed down. Participants also suggested that more different jets could be added for greater variation. Participants commented on how the device could also have other uses beyond fireworks, without providing concrete examples.

This study was conducted in person by the researchers who developed Feeling Fireworks, and it is possible that this could lead to some bias in the participants' responses. However, we believe that the benefits of conducting this study in person and in a conference environment outweigh this effect, through being able to answer questions from participants in great depth and also gaining new insights.

Table 1: List of firework effects. Each effect was available in the user study as a visual clip, as a full-screen tactile effect, and as a center-screen tactile effect. The symbol '→' indicates a sequence, with one effect ending and another effect beginning. The symbol '+' indicates superimposed effects.

	Description
1	Ascending rocket → explosion
2	Sequential ascending rockets
3	Ascending diverging rockets → explosions
4	Sequential ascending diverging rockets
5	Ascending rocket → flower
6	Ascending rocket → descending flower in willow
7	Ascending rocket → explosion → crackle
8	Sequential ascending diverging rockets + crackle
9	Ascending rocket → explosion → 3 diverging rockets
10	Pinwheel with three jets moving circularly

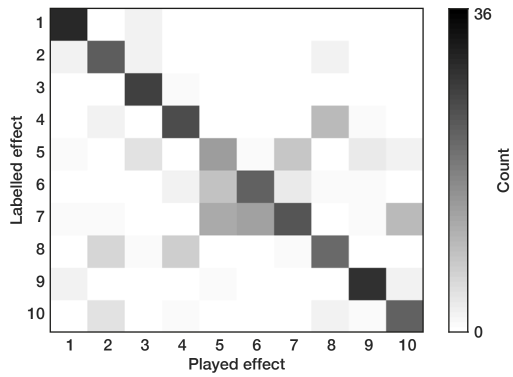

Figure 7: Confusion matrix from user study. The strong diagonal indicates that the tactile effects are meaningful analogs to visual effects. A small number of fireworks were confuse with each other, indicating that the tactile effects were too similar to discriminate.

User study with sighted users

A user study was carried out with sighted users to test whether the tactile effects were meaningful analogs for the corresponding visual fireworks. For this study, projection of visual fireworks on the screen was disabled. Participants were presented with a tactile firework, and asked to identify which firework it represented from a set of video clips.

The objective of this study is to quantify to what extent the visual fireworks and tactile fireworks are meaningful analogs—this is important as our goal is that BLV users experiencing the tactile fireworks should have a similar experience to friends and family experiencing visual fireworks. This therefore necessitates a study with sighted participants. Moreover, for going beyond the application of fireworks for BLV users it is relevant to understand how sighted participants perceive the effects.

The procedure was carried out in global full-screen mode and local center-screen mode as described in the previous section. After the study, participants were asked to complete a questionnaire.

Table 1 is the list of firework effects that were evaluated in the user study. The duration of the individual effects ranged from 5 s (effect 1) to 15 s (effect 6). Corresponding to each effect, there was one video clip, one full-screen tactile effect, and one center-screen tactile effect.

Procedure. Eighteen participants (seventeen male, mean age 29) took part in the study. Although it is possible that the uneven gender distribution may introduce unwanted bias, we consider this to be unlikely. The experimental procedure and the distinction between full-screen and center-screen tactile effects were explained. Participants were shown video clips of the ten fireworks in Table 1, and the clips were kept looping on a screen for reference throughout the study. The clips can be seen in the accompanying video.

The ordering of the full-screen and center-screen test was balanced across the participants. Users were told that the effects were full-screen/center-screen and were presented with the set of full-screen/center-screen tactile fireworks in random order, and asked to assign each to one of the video clips. Participants were able to explore the tactile effects for as long as desired before labeling the tactile-to-visual correspondence. The time taken for each response was recorded.

Results. The recognition results from the full-screen and center-screen tests are combined to generate the confusion matrix shown in Fig. 7. As indicated by the strong diagonal, performance is good, with 66 % of fireworks being correctly identified, versus 10 % by chance. This corresponds to a Cohen's kappa of 0.62, which indicates a *substantial* strength of agreement [32]. A small number of fireworks were misclassified frequently, indicating that the tactile effects were too similar to discriminate. Effects 5, 6 and 7 were confused and all involve a single rocket combined with the flower or crackling nozzle. Effects 4 and 8 were confused and both involve a sequence of rockets with the difference being background crackling.

There was no significant difference in recognition performance between full-screen and center-screen tactile effects. On average, participants spent just under 30 s per firework. There was a small increase in recognition performance (64 % to 67 %), and a decrease in taken time (32 s to 24 s), for a user taking the first test and second test in the study, as expected

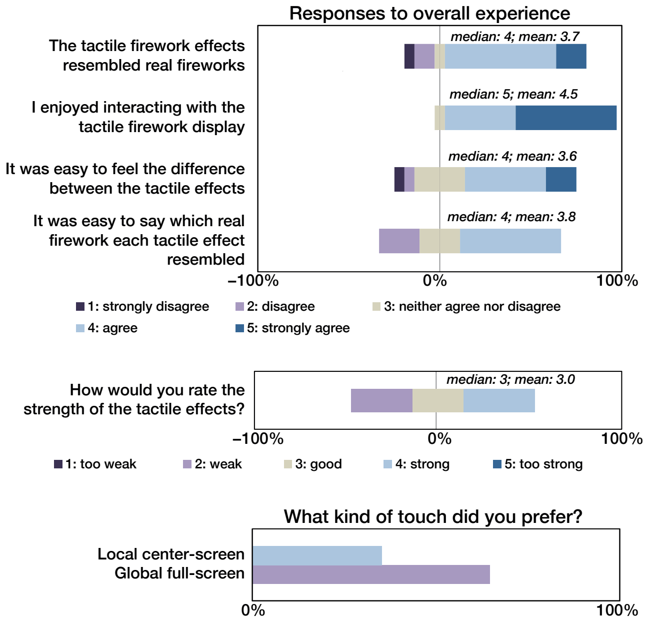

Figure 8: Sighted users' responses on overall experience, strength of tactile effects, and interaction modality.

due to familiarity. A t-test showed that this effect is significant, $t(314) = 4.2, p < 0.001$. Participants took significantly more time to label full-screen effects versus center-screen effects (30 s versus 27 s), $t(358) = 2.8, p = 0.006$.

Questionnaire. Participants were asked four questions about the interaction, and responses were recorded on a 5-point Likert scale. Participants were also asked if they preferred full-screen or center-screen fireworks, and about the strength of the firework effects. Results are presented in Fig. 8.

A summary is that the participant experience was positive with the enjoyment question receiving a high rating. Most participants perceived the tactile effects as resembling their corresponding visual fireworks. The majority of participants preferred full-screen effects, and the tactile strength of the effects was at an appropriate level.

The results from the BLV user study (Fig. 6) can be compared with those from the study with sighted users (Fig. 8)—overall the responses were similar. With regards to the strength of the effects, a higher proportion of the sighted users labelled the effects as 'weak' whereas the majority of BLV users labelled them 'good' or 'strong'. A small number of sighted users disagreed or strongly disagreed with the statement 'it was easy to feel the difference between the tactile effects' while no BLV users disagreed with this statement. (The comparison is not direct because the sighted users tried 10 tactile fireworks, and the BLV users tried the five most successful tactile fireworks only).

We take the positive response to the statements 'the tactile effects on the screen felt to me like real fireworks' and 'it was easy to feel the difference between the tactile effects' (in both user studies, Fig. 6 and Fig. 8), plus the quantitative results in Fig. 7, as indication that Feeling Fireworks provides a meaningful firework experience.

6 DISCUSSION

The goal of the work has been to provide a new and inclusive way for the BLV community to sample a firework show. Fundamental to making this a meaningful experience is that there is a genuine correspondence between a visual firework effect and its corresponding tactile effect, and a user study with sighted users indicated that this is the case. Moreover, both sighted and BLV users described Feeling Fireworks as an enjoyable experience.

Extensions: The current system allows user selection of individual fireworks. A further goal is to synchronise the effects with a live firework show, which is a feasible step for large firework shows that are pre-scripted and computer-controlled. User interaction on the screen is currently confined to button press but more complex and expressive interactions can also be achieved with a soft screen [47].

Insights about the tactile interface: Our tactile fireworks were designed by mapping the spatio-temporal patterns a user would see in the sky to the tactile screen. Global full-screen and local center-screen firework effects require different interaction modes—active-touch and passive-touch respectively—but our results show that users had similar performance in the two, with roughly two thirds of users preferring the global interaction mode. Although the performance was similar, participants commented on the different experience provided by the two modalities. The global effects were seen as more exploratory, but users would occasionally miss fireworks. The local effects were compared to watching a video. In a real-world scenario, users might choose either interaction modality or could be guided towards a particular modality—this must be kept in mind when designing the interaction experience.

Limitations: The haptic screen design presented here is well suited for large screens, and could readily be scaled up to wall-sized displays and full-body interaction. However, it is less suited for smaller screens and smaller devices such as handhelds or wearables. Moreover, while the water jets allow for very strong and dynamic tactile effects to be created, as is required for fireworks, different nozzle designs would be required for producing very subtle and soft effects.

One limitation we observed is that when multiple effects are combined on the screen, the sense of touch quickly becomes saturated and it is difficult to perceive the details of the individual effects. This is a limitation of the tactile perception modality, but should be kept in mind when designing tactile effects for this device and more generally when going from vision to touch. A targeted psychophysical evaluation of the display, with the goal of better understanding the tactile channel, would be an interesting avenue for future work.

We require the user to be in contact with the screen in order to produce tactile effects, unlike some recent technologies e.g. using ultrasound for tactile stimulation without contact [6]. However, this affords more active interactions (the user must touch the screen) and we believe it is therefore well-suited for our application.

Generality and broader applications: The technology presented here provides large-screen dynamic tactile effects, which can be either localized (rockets) or distributed over a large area (flowers, explosions). The experience is aesthetic as demonstrated through the good correspondence between tactile and visual fireworks. This shows potential for broader applications.

The work of Kim et al. [28] is inspirational on educational possibilities for a tactile screen, such as conveying concepts like height, speed and divergence.

The use of balloons by deaf people to feel music [36] suggests that a tactile-visual screen might provide a platform for a tactile-visual musical experience, a related technology being the Sound Shirt [19].

One could envisage a tabletop real-time strategy game (the technology would also work with a horizontal screen) using the device as a large soft touch screen. The water jets could be used to produce strong and localized haptic effects, e.g. for explosions or casting spells. This could also have applications in exergaming [9], i.e. electronic games where the users are required to excert themselves physically.

With its combination of tactile, visual and auditory stimuli, the device also presents interesting opportunities for new multi-modal interaction techniques, and could for example also be well suited for sensory rooms.

Combining the input and output modalities of the device, another possible application would be remote social touch [52] between two users with identical hardware setups. The strength and fast dynamics of the display would be a clear advantage, enabling more compelling and immersive experiences.

7 CONCLUSION

This work has presented a novel design of tactile screen that supports fast dynamic tactile effects at high spatial resolution, is scalable, and low-cost. The approach was demonstrated in Feeling Fireworks, an application that provides an extra dimension to a firework show for BLV users. A user study with sighted users demonstrated that the tactile firework effects are meaningful analogs to visual firework effects. Both with BLV and sighted users, the user studies show that Feeling Fireworks is both enjoyable and informative, thereby making it successful as an inclusive firework experience that can be shared by all.

ACKNOWLEDGMENTS

We thank the focus group and user study participants for their invaluable feedback, Maurizio Nitti for help with artwork, and the anonymous reviewers for their insightful comments. EK was supported by the European Commission, Horizon 2020 Framework Programme, H2020-ICT-645599.

REFERENCES

[1] Aira website. 2018. aira.io/

[2] Olivier Bau, Uros Petrevski, and Wendy Mackay. 2009. BubbleWrap: a textile-based electromagnetic haptic display. In *Proc. SIGCHI Conference on Human Factors in Computing Systems, Extended Abstracts.* ACM, 3607–3612.

[3] O. Bau, I. Poupyrev, A. Israr, and C. Harrison. 2010. Tesla Touch: Electrovibration for touch surfaces. *Proc. ACM Symposium on User Interface Software and Technology* (2010), 283–292.

[4] Jens Bornschein, Denise Bornschein, and Gerhard Weber. 2018. Comparing Computer-Based Drawing Methods for Blind People with Real-Time Tactile Feedback. In *Proc. SIGCHI Conference on Human Factors in Computing Systems.* ACM, 115.

[5] Bristol Braille. 2019. http://www.bristolbraille.co.uk/

[6] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proc. ACM Symposium on User Interface Software and Technology.* ACM, 505–514.

[7] Dot Watch. 2019. https://www.dotincorp.com/

[8] eSight. 2017. eSight. https://www.esighteyewear.com/.

[9] Exertion Games Lab. 2019. http://exertiongameslab.org/

[10] Vocal Eye. 2015. FingerWorks. www.vocaleye.ca/fireworks

[11] F. Follmer, D. Leithinger, A. Olwal, A. Hogge, and H. Ishii. 2013. inFORM: Dynamic physical affordances and constraints through shape and object actuation. *Proc. ACM Symposium on User Interface Software and Technology* (2013), 417–426.

[12] Sean Follmer, Micah Johnson, Edward Adelson, and Hiroshi Ishii. 2011. deForm: an interactive malleable surface for capturing 2.5 D arbitrary objects, tools and touch. In *Proc. ACM Symposium on User Interface Software and Technology.* ACM, 527–536.

[13] Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. 2012. Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. In *Proc. ACM Symposium on User Interface Software and Technology.* ACM, 519–528.

[14] FWsim. 2017. FWsim firework simulation. www.fwsim.com.

[15] Louis H Goldish and Harry E Taylor. 1974. The Optacon: A Valuable Device for Blind Persons. *New Outlook for the Blind* 68, 2 (1974), 49–56.

[16] Timo Götzelmann. 2016. LucentMaps: 3D printed audiovisual tactile maps for blind and visually impaired people. In *Proc. ACM SIGACCESS Conference on Computers and Accessibility.* ACM, 81–90.

[17] Graphiti. 2019. https://www.aph.org/graphiti/

[18] Richa Gupta, M Balakrishnan, and PVM Rao. 2017. Tactile Diagrams for the Visually Impaired. *IEEE Potentials* 36, 1 (2017), 14–18.

[19] Junge Symphoniker Hamburg. 2016. Sound Shirt. https://sound-shirt.jimdo.com/english-1/

[20] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. Shapeclip: towards rapid prototyping with shape-changing displays for designers. In *Proc. ACM Conference on Human Factors in Computing Systems*. ACM, 19–28.

[21] Chris Harrison and Scott E Hudson. 2009. Providing dynamically changeable physical buttons on a visual display. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 299–308.

[22] HIMS, Inc. 2017. Braille Sense U2 QWERTY. https://hims-inc.com/products/braille-sense-u2-qwerty/.

[23] HyperBraille. 2019. http://hyperbraille.de/?lang=en

[24] A. Israr and I. Poupyrev. 2011. Tactile Brush: Drawing on skin with a tactile grid display. *Proc. SIGCHI Conference on Human Factors in Computing Systems* (2011).

[25] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proc. Conference on Computer Graphics and Interactive Techniques*. ACM, 469–476.

[26] Yvonne Jansen, Thorsten Karrer, and Jan Borchers. 2011. MudPad: tactile feedback for touch surfaces. In *Proc. SIGCHI Conference on Human Factors in Computing Systems, Extended Abstracts*. ACM, 323–328.

[27] Jingun Jung, Eunhye Youn, and Geehyuk Lee. 2017. PinPad: Touchpad Interaction with Fast and High-Resolution Tactile Output. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2416–2425.

[28] Jeeeun Kim and Tom Yeh. 2015. Toward 3d-printed movable tactile pictures for children with visual impairments. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2815–2824.

[29] Philip Kingsley. 2012. *eTable: A haptic elastic table for 3D multi-touch interactions.* Master's thesis. University of Bristol.

[30] Espen Knoop and Jonathan Rossiter. 2015. A compliant soft-actuator laterotactile display. *Smart Materials and Structures* 24, 4 (2015), 045034.

[31] Espen Knoop and Jonathan Rossiter. 2015. The tickler: a compliant wearable tactile display for stroking and tickling. In *Proc. SIGCHI Conference on Human Factors in Computing Systems, Extended Abstracts.* ACM, 1133–1138.

[32] Gary G. Koch, J. Richard Landis, Jean L. Freeman, Daniel H. Freeman, and Robert G. Lehnen. 1977. A General Methodology for the Analysis of Experiments with Repeated Measurement of Categorical Data. *Biometrics* 33, 1 (1977), 133–158.

[33] Ki-Uk Kyung, Jeong Mook Lim, Yo-An Lim, Suntak Park, Seung Koo Park, Inwook Hwang, Seungmoon Choi, Jongman Seo, Sang-Youn Kim, Tae-Heon Yang, et al. 2011. TAXEL: Initial progress toward self-morphing visio-haptic interface. In *World Haptics Conference (WHC), 2011 IEEE*. IEEE, 37–42.

[34] Susan J Lederman and Roberta L Klatzky. 2009. Haptic perception: A tutorial. *Attention, Perception, & Psychophysics* 71, 7 (2009), 1439–1459.

[35] B. Long, S. Seah, T. Carter, and S. Subramanian. 2014. Rendering volumetric haptic shapes in mid-air using ultrasound. *ACM Transactions on Graphics* 33, 6 (2014).

[36] Nature News. 2001. Deaf people use 'mind's ear' to process vibrations. http://www.nature.com/news/2001/011127/full/news011129-10.html.

[37] Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. 2017. Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE Transactions on Haptics* (2017).

[38] Yosra Rekik, Eric Vezzoli, Laurent Grisoni, and Frédéric Giraud. 2017. Localized Haptic Texture: A Rendering Technique based on Taxels for High Density Tactile Feedback. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 5006–5015.

[39] D. R. Sahoo, K. Hornbæk, and S. Subramanian. 2016. TableHop: An actuated fabric display using transparent electrodes. *Proc. SIGCHI Conference on Human Factors in Computing Systems* (2016), 3767–3780.

[40] Samuel B Schorr and Allison M Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3115–3119.

[41] Lei Shi, Ross McLachlan, Yuhang Zhao, and Shiri Azenkot. 2016. Magic Touch: Interacting with 3D Printed Graphics. In *Proc. ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 329–330.

[42] L. Shuai, Y. Kuang, and Z. Zhou. 2005. Research on robot tactile display based on water jet technology. *Robotics and Biomimetics (ROBIO). 2005 IEEE Int. Conf.* (2005).

[43] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2017. Sparkle: hover feedback with touchable electric arcs. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3705–3717.

[44] Saiganesh Swaminathan, Thijs Roumen, Robert Kovacs, David Stangl, Stefanie Mueller, and Patrick Baudisch. 2016. Linespace: A sensemaking platform for the blind. In *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2175–2185.

[45] Tactile Labs. 2017. Haptuator Mark II. http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/.

[46] Brandon Taylor, Anind Dey, Dan Siewiorek, and Asim Smailagic. 2016. Customizable 3D printed tactile maps as interactive overlays. In *Proc. ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 71–79.

[47] Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2014. User-defined gestures for elastic, deformable displays. In *Proc. Int. Working Conference on Advanced Visual Interfaces*. ACM, 1–8.

[48] Dzmitry Tsetserukou, Alena Neviarouskaya, Helmut Prendinger, Naoki Kawakami, and Susumu Tachi. 2009. Affective haptics in emotional communication. In *Int. Conf. Affective Computing and Intelligent Interaction*. IEEE, 1–6.

[49] Jessica Tsimeris, Colin Dedman, Michael Broughton, and Tom Gedeon. 2013. ForceForm: a dynamically deformable interactive surface. In *Proc. ACM Int. Conf. Interactive Tabletops and Surfaces*. ACM, 175–178.

[50] Marlon Twyman, Joe Mullenbach, Craig Shultz, J Edward Colgate, and Anne Marie Piper. 2015. Designing wearable haptic information displays for people with vision impairments. In *Proc. Int. Conf. on Tangible, Embedded, and Embodied Interaction*. ACM, 341–344.

[51] Thorsten Völkel, Gerhard Weber, and Ulrich Baumann. 2008. Tactile graphics revised: the novel brailledis 9000 pin-matrix device with multitouch input. In *Int. Conf. Computers for Handicapped Persons*. Springer, 835–842.

[52] Rongrong Wang, Francis Quek, James KS Teh, Adrian D Cheok, and Sep Riang Lai. 2010. Design and evaluation of a wearable remote social touch device. In *Int. Conf. Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction*. ACM, 45.

[53] Wayfindr. 2017. Wayfindr. https://www.wayfindr.net/.

[54] Be My Eyes website. 2018. www.bemyeyes.com

[55] Laura Winfield, John Glassmire, J Edward Colgate, and Michael Peshkin. 2007. T-pad: Tactile pattern display through variable friction reduction. In *World Haptics Conference*. IEEE, 421–426.

[56] Cheng Xu, Ali Israr, Ivan Poupyrev, Olivier Bau, and Chris Harrison. 2011. Tactile display for the visually impaired using TeslaTouch. In *Proc. SIGCHI Conference on Human Factors in Computing Systems, Extended Abstracts*. ACM, 317–322.

[57] Juan Jose Zarate, Olexandr Gudozhnik, Anthony Sébastien Ruch, and Herbert Shea. 2017. Keep in Touch. In *Proc. SIGCHI Conference on Human Factors in Computing Systems, Extended Abstracts*. ACM Press, 349–352.