Active PinScreen: Exploring Spatio-Temporal Tactile Feedback for Multi-Finger Interaction

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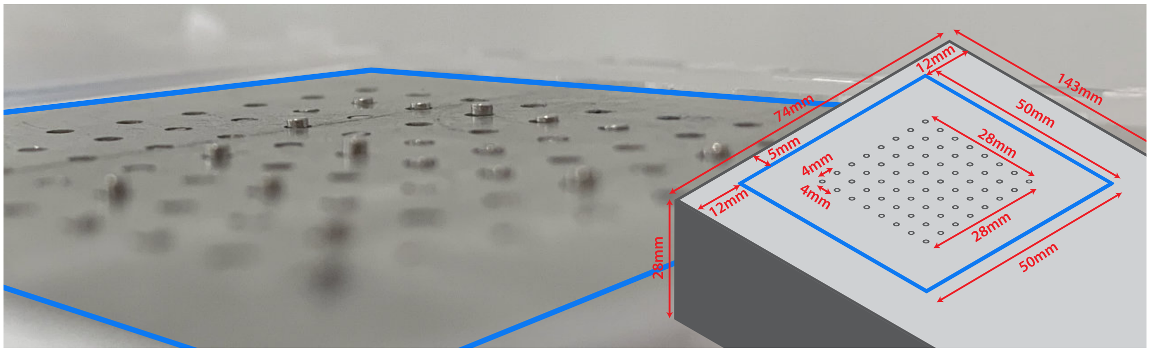

Fig. 1. Active PinScreen is a tactile feedback grid that can be mounted on the back of a mobile device to give spatio-temporal direction information over multiple fingers, synchronised with the digital content on the phone's touchscreen. The main image shows a close-up view of the device's 1 mm diameter pins. The small nature of the Active PinScreen (as seen in the schematic inset to the right; blue highlighted area corresponding to main photo) affords the ability to fit comfortably on the back of a standard touchscreen device to provide high-precision feedback to multiple fingers at once.

Multiple fingers are often used for efficient interaction with handheld computing devices. Currently, any tactile feedback provided is felt on the finger pad or the palm with coarse granularity. In contrast, we present a new tactile feedback technique, *Active PinScreen*, that applies localised stimuli on multiple fingers with fine spatial and temporal resolution. The tactile screen uses an array of solenoid-actuated magnetic pins with millimetre scale form-factor which could be deployed for back-of-device handheld use without instrumenting the user. As well as presenting a detailed description of the prototype, we provide the potential design configurations and the applications of the Active PinScreen and evaluate the human factors of tactile interaction with multiple fingers in a controlled user evaluation. The results of our study show a high recognition rate for directional and patterned stimulation across different grip orientations as well as within- and between- fingers. We end the paper with a discussion of our main findings, limitations in the current design and directions for future work.

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CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

Additional Key Words and Phrases: Mobile Interaction; Haptic; Tactile Interfaces

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1 INTRODUCTION

Reading the reviews of almost any recent mobile phone launch, it is clear there is a widespread sense that these devices have reached something of a peak in terms of their physical design. Recently dismissed in the media at launch as *"more black rectangles"*,[1] today's cutting-edge devices are no-longer met with anything close to the level of excitement or anticipation that accompanied their earlier iterations. Consequently, there is an increasing focus on new form factors and novel interaction styles from both device manufacturers and engineering and HCI researchers. In particular, interaction modalities that are not focused solely around a touchscreen are experiencing a resurgence. Consider, for example, the renewed interest in haptic feedback, both on [13, 23] and around[2] a mobile device.

Current on-device haptics are relatively coarse in their output, often producing only a single point of feedback. That is, an interaction on-screen will lead to a tactile pulse to confirm an action, or a vibration will be generated to give a simple alert in cases when the user is not actively using the device. Even when feedback is more advanced, the sensation is typically either on a global scale (for example, a whole device vibrating to produce patterns linked to particular meanings [6]); or, nuanced and precise output, but directed to a single finger [13].

In this work, we turn to explore the potential for multiple areas and patterns of tactile output that are produced concurrently yet felt independently. Our design—*Active PinScreen*—is a micro-grid of 64 (8×8) actively-actuated metal pins. Each millimetre-sized actuator can be individually addressed and energised. The prototype, as illustrated in Fig. 1, is incorporated into the back of a mobile casing, and is able to create tactile, patterned outputs on the middle and distal phalanges of multiple of its holder's fingers at the same time (typically ring, middle and index). The prototype can feasibly fit within the casing of a standard smartphone, and is able to apply localised stimuli with fine spatial and temporal resolution. In addition, while we focus on the use of Active PinScreen on a smartphone, we also consider it suitable for use on other handheld or mobile devices, such as game controllers or smartwatches.

There is a rich history of research in this space, with many avenues of tactile feedback widely explored, as detailed in the related work section below. Our research goes beyond previous work with two key contributions. Firstly, we deploy the new richness in micro output that our novel hardware can generate in order to provide haptic information to multiple fingers *simultaneously*. Secondly, we miniaturise the haptic actuator apparatus so that it could potentially be deployed on the back of a smartphone-sized device. As shown later in Fig. 5, the pin array, controller circuitry and power supply all currently fit within a casing that could be attached to the back of a mobile device. We have released our hardware and circuit designs (with accompanying microcontroller code) as an open-source toolkit [3] to enable others to build upon this work and integrate it into actual mobile devices, which would further reduce the physical size of the hardware.

In the rest of this paper, we begin by situating our research amongst previous work in mobile haptic surfaces, mobile tactile interaction, pin-array display, tactile actuation methods and stimulation patterns, using this as inspiration to

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[1] https://economist.com/business/2017/03/02/conformity-nostalgia-and-5g-at-the-mobile-world-congress; [2] https://ultrahaptics.com

[3] https://github.com/FITLab-Swansea/ActivePinScreen

generate a series of potential design configurations for a multi-finger haptic feedback device. We then describe the technical design and implementation of our novel hardware prototype, and report on an evaluation designed to test the extent to which the Active PinScreen is able to provide rich and recognisable feedback. We conclude by discussing the potential and future developments of the work.

2 RELATED WORK

Modern mobile devices typically utilise touchscreens or controllers to facilitate multi-touch interaction. This interaction modality has the effect that the majority of the device—and, indeed, most of the user's fingers—remain idle, particularly those fingers responsible for holding the device itself. Unsurprisingly, then, haptic feedback has long been considered a popular modality for mobile device interaction. Tactile feedback can be felt by all unused fingers, and benefits from utilising the vacant part of the device to provide potentially rich dimensions which can be configured for a variety of expressions.

Current types of tactile feedback available to users are normally limited to vibration pulses given by the entire device using actuators or motors mounted under (or on) the surface of the device. Even though the length and repetitions of these stimuli can normally be programmed to create customised temporal tactile sequences that can be felt over multiple fingers, they are still low in spatial resolution, and struggle to provide detailed tactile feedback such as texture or small-scale patterns. Our approach, the Active PinScreen, has been created to address these issues. The following sections describe its novelty via a review of the current literature.

2.1 Mobile haptic surfaces

Mobile touchscreen surfaces with haptic feedback have opened up a new modality to enrich human-computer interaction [21]. Providing tactile feedback on touchscreen mobiles can support eyes-free information interaction, such as, for example, in MagTics [34], which provided both static and dynamic haptic eyes-free feedback on the surface of a wearable interface (e.g., the strap of a smartwatch). Other examples, such as haptic output on the surface of a handheld controller, allow a user to feel the 3D surfaces, textures and the output force of virtual objects [3]. However, different from these mobile surfaces, we focus on providing haptic interaction on the back of smartphones, making use of currently underused surface areas (i.e., the back of the device) and extremities (the fingers holding the device). While previous work has already made use of vibration motors, 3D-printed overlays and deformable prototypes, our work has miniaturised the hardware for the first time to afford its integration into a portable phone case and allowing it to sit comfortably in a user's hand.

2.1.1 Vibration. SemFeel [54], Omnivib [1], and T-mobile [50] provided spatiotemporal tactile patterns by vibrating a series of motors attached on different areas of handheld devices. Activating these motors in sequence can provide users with feedback for a variety of scenarios – for example, left-then-right vibration to indicate a "next page" action. Some use-cases of this type of technology include SpaceSense [53] which used vibration to present geographical information, and Activibe [6] which used vibration pulses to present primary activity feedback. However, due to the relatively large size of the motors used in these examples, they were tested only on body areas far larger than the phalanges of fingers, such as the palm, arms, thigh and waist. The high resolution and miniaturisation of our approach allows us to target the sensitive areas of fingertips with a fine level of granularity.

2.1.2 Touch overlays. Attaching a 3D-printed overlay on the surface of a display can make everyday interfaces accessible for eyes-off interactions [14]. TacTILE [16], for example, proposed a novel tool for creating these overlays for arbitrary graphics (e.g., graphs, pictures, maps). Touchplates [26] proposed a method of designing cutout overlays based on the UI beneath. These overlays guide the user when they touch the physical layout on the screen. Similar kinds of "tactile guides" on top of touch screens have been used for controller apps [29], digital reading [11] and navigation [44]. However, once this kind of layout is created it is permanently fixed. This approach also always requires the user to move their finger to explore the layout, which may be inconvenient for situations when the user is on the move.

2.1.3 Deformable buttons. Deformable buttons combine the benefits of digital and physical to provide low attention and vision-free interactions through their changeable tactile clues. They have been used, for example, when providing haptic feedback for controlling a visual display [15], or to explore haptic and more expressive notifications [17, 18]. However, the hardware required to implement deformable buttons can limit portability, and can be challenging or impractical to minimise.

2.2 Mobile tactile interaction

Considering the smartphone surface, other researchers have proposed ways of providing haptic feedback on the front, edge and the back of the device.

Braille-based designs have been constructed for communication [33] and a window system [37]. Each braille key has a set of tactile dots on it to represent a character or word, and allows a user to read by touching the braille keys of the display panel sequentially. However, these tactile surfaces blocked the screens which were originally used to display visual information.

Haptic Edge Display [23] used a single edge of a mobile device to provide haptic feedback. An array of small piezoelectric actuators in a line on the side of the display was able to give force feedback to multiple fingers. Similarly, Luk et al. used an array of piezoelectric actuators to give different temporal stimuli on a finger pad with lateral skin stretch [32]. ShiftIO [42] used small magnets (actuated by an array of solenoids) to equip the edges around a smartphone as configurable tactile elements. The elements can sense touch input and give haptic notifications as a "bump" to the user's hand as they grip the device. However, these haptic edge surfaces either required the user's visual attention or were limited by the holding pose that was necessary.

Back-of-device interaction is one way that these issues have been overcome. RearType [39], for example, explored the ability of the fingers, maximising the use of the front display for visual output and adding split and rotated keyboard layouts on the back of a smartphone. HaptiCase [8] helped users to know the location of their fingers on a rear case by feeling tactile landmarks on the back of the smartphone. Like these works, by taking advantage of back-of-device interaction, the Active PinScreen focuses on implementing reliable sensation output on the back of a smartphone. Unlike these systems, however, our design provides dynamic feedback that is controlled by the mobile device itself.

2.3 Pin-array displays

Our work was inspired by pin-array displays. For example, Summers et al. [43] used 100 piezoelectric actuators to drive 100 contactor pins arranged in a $1 \times 1\,\mathrm{cm}$ square matrix which covered a fingertip. Participants were asked to identify the direction of motion: up, down, left or right. In all cases the pins moved from one side of the array to the other in one second (i.e., at a speed of $1\,\mathrm{cm\,s^{-1}}$). The experiment tested the recognition rate at frequencies of 40 Hz and 320 Hz. It showed that the position of moving stimuli on the skin is more accurately perceived at 320 Hz than at 40 Hz. However, the hardware required was relatively large, and not mobile. A similar work [27], integrated 61 electrodes with 1.2 mm diameter on the back of a smartphone, investigating how well the user can recognise four linear directions and four shape patterns (square, circle, triangle and cross). The research found when the presentation finger and operating finger were both on the same hand, there was an accuracy and speed advantage.

Tactons [5] proposed tactile displays for structured, abstract message communication, exploring the parameters which may cause different perceptions of a tactile display. The parameters included the frequency, amplitude, waveform, duration, rhythm and body location. However, the authors did not evaluate which frequency, amplitude or other parameters can be better perceived in detail. BrailleDis [47] consisted of a matrix of 60 × 120 pins. The proposed touchpad was actuated via piezoelectric actuators and the pins were sited in a concave tactile surface. Both the engineering and HCI design challenges were discussed, but no evaluation was conducted.

PinPad [24] consisted of a 40 × 25 array of tactile pins. Each pin of the PinPad was separated 2.5 mm away from others, based on the tactile spatial threshold of the fingertip. The PinPad's scan rate was about 11 Hz. However, parameters such as the stimulation frequency, pin movement, speed and output force were not reported. A key difference between these previous works and our Active PinScreen is that the previous designs require the user to move their finger across the pin array to feel feedback, which is unsuitable in our scenarios. Active PinScreen is intended to provide feedback with the user's fingers stably positioned on the rear of the device.

2.4 Actuation methods

Instead of vibration of the entire device [36, 46], tactile displays using a wide variety of actuation methods have been used for providing different localised sensations. For example, HamsaTouch [25] converts a visual image to a tactile image using an electro-tactile display of 512 electrodes. A linear grouping of actuators is used to form a slider on one side of a mobile for list selection, scrolling, direction signalling and background status notification [32]. Strasnick et al. [41] present a method of using switchable permanent magnetic actuators for these kinds of displays. To enrich the user experience rather than convey specific interface or content information, Tactile Brush [22] enables two-dimensional tactile movement sensations via a sparse array of actuators.

Instead of relying on electro-mechanical transmission, alternative forms of actuation have been proposed. For example, Sadeghi et al. present a micro-hydraulic actuator which consists of 3 × 3 and 4 × 4 arrays of fluid-driven actuator cells offering high displacement and force [38]. However, usage of these displays may be hindered by the power available. Soft actuators [30] provide stimulation on the human skin via a polymer allowing the device to have qualities of softness to touch, adding flexibility and enabling size minimisation. We take a different approach to these works, using micro solenoid-actuated magnetic pins with millimetre scale form-factor.

2.5 Tactile simulation patterns

Khurelbaatar et al. created an electrotactile display at the back of a phone to give direction and spatial patterns on a fingertip using an array of small electrodes [27]. Another more recent tactile display [40] used 3 × 3 poke and vibrotactile arrays which can be worn around the wrist to give four different direction patterns. HaptiVec [7] used an array of 3 × 5 tactile pins (with an average pin spacing of 25 mm) actuated by commercial linear solenoid actuators in the handles of two custom VR type controllers to give haptic feedback with direction information. However, these patterns are more coarse compared with our Active PinScreen.

Beside directional patterns, previous work explored tactile simulation patterns of different force, frequency and three-dimensional shapes. HapCube used three voice-coil actuators to give tangential and normal pseudo-force feedback at the fingertip [28]. WAVES used voice coil actuators on the fingers to give three-dimensional translation and rotation cues with asymmetric vibration on multiple fingers [10]. Pin array displays such as [51], with a 6 × 5 array, and

Tiny-Feel [52], with a 3×3 arrays actuated by piezoelectric bimorphs, provide tactile patterns of different frequency. TextureTouch [3] provided haptic renderings of three-dimensional shapes and structures onto the user's finger.

3 DESIGN CONFIGURATIONS

After reviewing previous research, we developed the concept of a mobile, multi-finger haptic feedback device based on an actuated micro-pin array. However, this core design could be tailored to provide a range of options from both fabrication and use-case perspectives. In order to guide the construction of the prototype that we describe in the rest of this paper, we needed to carefully consider the parameters available, and their impact on or use within the device itself. Here we outline the factors we considered in our own design, and the further configurations possible in each case.

3.1 Form Factor

The *size* and *shape* of the pins and their enclosing array, and the *spatial resolution* (i.e., the separation between the pins in the array) and *stimulation* are the key form factor parameters that can be varied to provide effective haptic feedback on multiple fingers.

Size: The size (i.e., length and width) of an Active PinScreen device could be tailored according to the size of the enclosing device that encloses it (such as a smartphone or a game controller). The pin array could be designed to cover the entire area of the user's grip; or, just the location of the targeted fingers if the typical grip position is relatively fixed.

Shape: Adapting the shape of an Active PinScreen device to the enclosing device could also lead to better integration and precise feedback. Again, the user's grip needs to be considered on handheld devices in order to position the tactile pins at the correct target locations or fingers. For example, users often grip a game controller in a consistent manner, whereas grip may change significantly on a smartphone. Further, although our realised design is a square, there is no underlying requirement for this to be the case. More unique or imaginative designs (e.g., star, circle, emoticon etc.) are entirely plausible.

Spatial Resolution: The optimal physical separation between actuated pins is primarily driven by the expected use cases of the device. Providing a 2.5D or 3D profile on a smartphone (e.g., like the table-top system of [12]) would require an Active PinScreen with a relatively higher resolution. Providing discrete sensations such as mimicking raindrops falling on the hand, could be achieved using an Active PinScreen with a lower resolution. Further, in addition to the flexibility of shape described above, the distribution of pins could also be non-uniform (i.e., concentrated in some areas more than others).

Stimulation: The Active PinScreen is capable of providing tactile stimulation both within a single finger and across multiple fingers. However, the stimulation it provides can be customised to meet users' needs. For example, to provide feedback that is robust to grip changes, inter-finger (i.e., across multiple fingers) stimuli could be designed. The stimuli are not reliant on the position and orientation of the individual fingers; rather, users explore a spatio-temporal pattern with multiple fingers using their preferred position and grip orientation. Our Active PinScreen design distributes pins in such a way that multiple fingers are covered by a set of pins about 4 mm apart (from each centre) for many possible grip orientations.

4 ACTIVE PINSCREEN PROTOTYPE

We built a prototype Active PinScreen as shown in Fig. 1 and Fig. 5 to determine the effectiveness of pin-arrays for multi-finger tactile stimulation on the back of mobile devices. The 8×8 array of pins on the prototype are uniformly distributed over an area of 28×28 mm. The prototype is about 67.5g and the whole device is 225g (including the battery

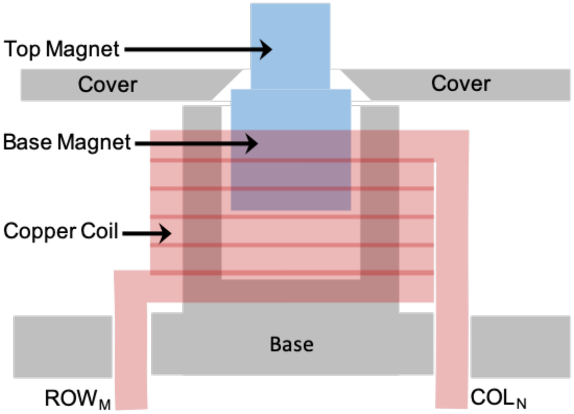

Fig. 2. A diagrammatic illustration of an individual pin unit in our Active PinScreen. The device contains 64 of these units in a 28×28 mm 8×8 matrix configuration, each directly addressable by row and column number.

and the case). A schematic of an individual pin unit with its linear solenoid actuator and plunger is shown in Fig. 2. The plungers—the moving pins of the Active PinScreen—are magnetic, and consist of two permanent neodymium magnets. The base magnets have a diameter and thickness of 1.5 mm, and slide through the air-core of the solenoid, trapped inside by the unit's top-cover. The top magnets are adhered to the base magnets, and have a diameter and thickness of 1 mm. When activated, these magnets emerge through the unit's cover and produce the tactile stimulation effect on the user's fingers.

The base is made of 8 mm acrylic, and the top cover of the device is a 2 mm aluminium plate. The inner tube and the air core for the solenoid in the base plate, and the 1.35 mm holes in the top plate are precisely cut using a CNC machine. A 32 gauge copper wire is wound approximately 25 turns to make each solenoid in the array. The coil ends of each solenoid are connected in rows and columns with a diode and two transistors (N- and P-type MOSFET) used to switch an active-matrix configuration as shown in Fig. 2. The solenoids are actuated one-at-a-time using a Microchip 18F47J53 8-bit microcontroller, with active matrix layouts transferred via Bluetooth from a smartphone.

Although the prototype's solenoids are in practice activated one-by-one, their fast response time (see Fig. 3), combined with pulse-width modulation means that this is imperceptible to the user. As a result, users are able to feel multiple pins simultaneously, affording us a larger surface area of activated pins at any one time. In order to achieve this sensation, however, it was important to consider the energy being injected into the system, as the coils are wound onto sub-millimetre thin hollow pillars of acrylic, within which the magnets oscillate. It is difficult for any heat generated within the coils (and also within the magnets themselves through inductive heating/eddies etc.) to dissipate to the environment. By experimentation, we settled on a maximum coil 'on-time' of 1 ms, with a maximum (long-term) of 30 Hz per coil. In this way, coils are less likely to overheat. The response time of the pin measured using a vibration sensor is shown in Fig. 3. The pin pokes the finger for 1 ms. The oscillation is the natural response of the vibration sensor due to the pulsed input. The behaviour of the pin in contact with the finger's skin will depend on the mechanical characteristics of the skin itself.

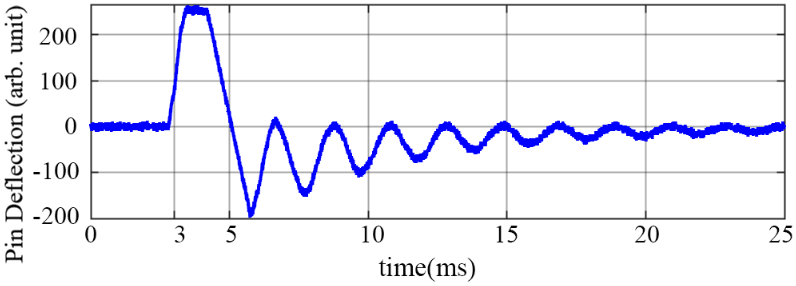

Fig. 3. The mechanical response of the Active PinScreen's pins to a 1 ms pulse measured using a vibration sensor. The pin contacts the user's skin for 1 ms.

4.1 Usage

The main goal in creating the Active PinScreen was to provide users with both directional and patterned stimuli to facilitate a variety of uses on the back of a device (see Section 2.2). In order to create these types of stimuli, we needed to generate a sequence of activated pins in the following way:

(1) Define a block pattern, which is known as a *frame*. Each pin in a frame will be activated simultaneously (or seemingly so from the user's perspective, but actually by careful design of the pulse widths and duty cycles of each pin as described below);
(2) Define the actuation time of each frame, known as $time_{actuation}$, which is the time each frame continues to be active for;
(3) Define the frame-to-frame delay, known as $time_{delay}$, which refers to the pause between each frame being actuated;
(4) Create a directional pattern by 'drawing' each frame on the pin array;
(5) Using the frame and parameters $time_{actuation}$ and $time_{delay}$, run the stimuli in sequence (i.e., frame by frame) until the pattern is complete.

This technique is used in the three studies included in the user evaluation that we describe hereafter (see Section 5), where we use a frame size of 1×3 pins (study 1), 2×3 (study 2) and 3×3 (study 3). Figure 4 illustrates an example of a left-to-right directional pattern using a series of four 2×3 frames.

4.2 Prototype configuration

The Active PinScreen has several other configurable parameters that required careful consideration to provide optimal tactile stimulation for users. As part of a small technical evaluation to discover the appropriate set of parameters for our prototype, we conducted several pilot studies with participants and research team members of the following:

Frequency We experimented with different pulse widths and duty cycles of the solenoid actuation signal and found the optimal to be 40 Hz actuation signal with 4 % duty-cycle.

Output Force We also experimented with the effect of the force applied by the pins; that is, the strength the stimuli on tactile feedback using different pulse widths and duty-cycles of the solenoid actuation signal. The average force of the device's effective tactile stimuli could be increased in three-ways. That is, either by increasing the duty-cycle or the peak of the current passing through the solenoid actuator, to vibrate the pins at a higher

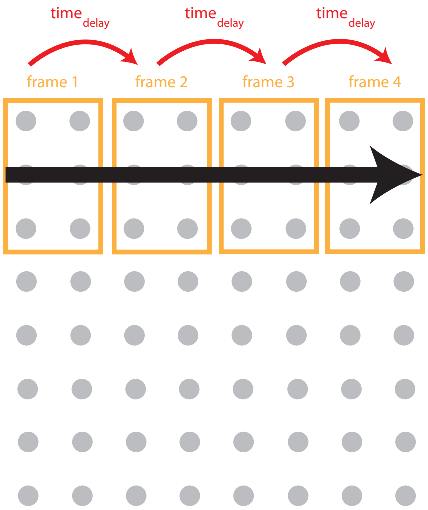

Fig. 4. An example of the sequence of a left-to-right directional pattern. The stimulation consists of four *frames*, each consisting of 2 × 3 (width × height) pins.

frequency or by using multiple pins within the two-point discrimination threshold [48] of the user (i.e., a frame as described above). We found during our trials that using small frames (i.e., of, $1 \times 3 - 3 \times 3$ arrays) and the pulse width and duty cycles described above provided the optimal output force.

Space Multiplexing We found that movement of the frames could be sensed better along the length of the phalanges than across their width. This could be due to the elliptic contact area of the finger phalanges and the sensitivity gradient along their major and minor axes. Sensing of all frames was low on the distal and proximal interphalangeal creases. This could be due to the low sensitivity of that region. The 2×3 (width × height) frames gave sharper sensation to recognise the movements along the fingers, whereas the 3×3 blocks of pins gave wider sensation to recognise the movements for different orientations of the fingers.

5 LAB STUDY

As we have described, the Active PinScreen allows a range of tactile stimulation patterns both within and between users' fingers. In order to determine the recognition rates of the tactile stimuli over the index and middle fingers, therefore, we conducted three user evaluations with 12 participants (6 females) aged between 20 and 52 (mean = 30.6, s.d. = 8.1), all right-handed. These studies were conducted to investigate within-finger recognition (study 1), inter-finger recognition (study 2) and the possible effect of grip orientation and pattern recognition (study 3). Each study lasted around 15 minutes (1 hour for the full experiment), and each participant was compensated for their time with a £10 gift voucher.

5.1 Procedure

We began each experiment with a two point touch test on both the index and middle finger of the participant's dominant hand as laid out by Won et al. [49]. Tactile spatial perception varies vastly from person to person [9, 35, 45], so the two point test was conducted to ensure all participants could perceive the same level of tactile sensation within

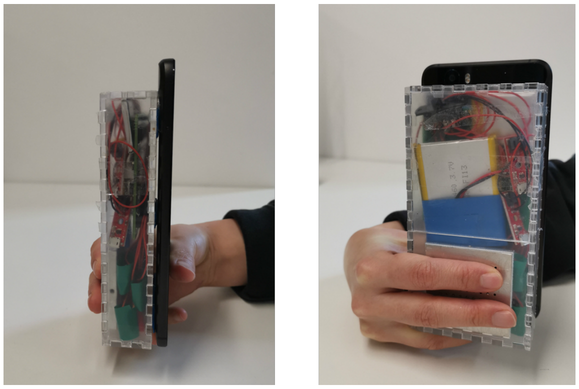

Fig. 5. During the experiment, participants were asked to rest their arm on the table while they held the Active PinScreen.

our experiment. A clinically healthy person should be able to recognise two points separated by 2 to 8 mm on their fingertips [4, 49]. We conducted the test, therefore, to ensure that any failure to properly identify the correct stimuli would be caused by the tactile stimulations themselves rather than simply being an issue with the participant's perception ability. Failure to successfully pass this test would exclude participants from continuing with the full experiment.

Upon passing the two point touch test, we then continued with a pre-study questionnaire to gather basic demographics before proceeding to carry out each study in turn (described below) in the same order for each participant.

During the study, the participants were asked to sit at a table and hold the prototype like a mobile phone with their dominant hand so they could easily feel the pin movements at the back of the device as shown in Fig. 5. The participants were asked to keep the position of their fingers fixed horizontally along the top three and bottom three rows of pins.

After each stimuli was completed, participants were asked to verbally report what pattern they felt (via a printed set of options), which we recorded in an anonymized spreadsheet. At the end of each study, we asked participants to fill in a questionnaire to elicit feedback about the strength and comfort of stimuli on a 5-point Likert scale. We also conducted a short interview to gather feedback about present performance and potential future features and applications of Active PinScreen devices.

5.2 Experimental Design

5.2.1 Within-finger recognition. In this experiment, we studied the effectiveness of recognising *within-finger* stimulation. Specifically, we were interested in whether the users could recognise multiple directional movements on individual fingers simultaneously. With this in mind, we asked participants to keep the position of their fingers fixed horizontally along the top three and bottom three rows of pins (as shown in Fig. 6 (left)), then provided them with two distinct directional movements at a time; either both in the same direction (as shown in Fig. 6 (a) and (b)) or in opposite directions (as shown in Fig. 6 (c) and (d)).

We used a frame size of 1×3 (width × height) to create each directional movement (in a total of 8 frames). The total pins activated in each trial are shown in blue in Fig. 6 (right). The speed was set at $15\,\mathrm{mm\,s^{-1}}$.

We began the study with a five minute training session which introduced each of the four sets of stimuli twice – once in the order shown in Fig. 6 (a–d) and once in a random order. The participants were then offered for any of the

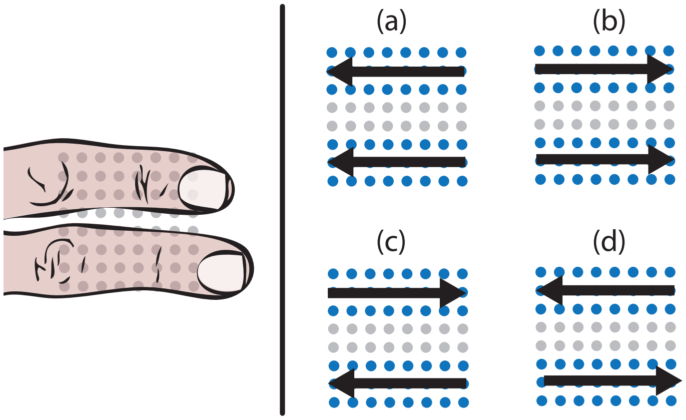

Fig. 6. Study 1: Within-finger recognition. The overview (left) shows the finger placement used in Study 1, and the sub-diagrams (a, b, c and d) show the stimuli provided to each individual finger. Blue dots indicate the active pins used in each trial, and the arrows show the direction of movement. Each movement was created by sequentially activating 1 × 3 blocks of pins (width × height) along each arrow.

stimuli to be repeated; most felt confident to begin after a single repetition. We then ran the study where each of the four stimuli were given to the participants 14 times in random order (56 times total).

Participants were told that each of the trial stimuli would match one of the four combinations shown in Fig. 6. They were provided with this information on a printed sheet and after each stimulation were asked to state which combination best matched what they felt (note: there was no way to answer "I don't know."). Any trial where the participant matched the correct direction (a, b, c or d) exactly, was classed as successful. The overall recognition rate for each direction-pair was calculated as the proportion of successful recognition trials.

5.2.2 Inter-finger recognition. In this study, we evaluated the effectiveness of recognising *inter-finger* stimulation. We were interested in whether participants could recognise different directional information across multiple fingers. To this end, we opted to again keep the participant's fingers fixed in a horizontal position along the top three and bottom three rows of pins (as shown in Fig. 7, left) but this time provide them with a single directional stimulation that spans two fingers (as shown in Fig. 7 a–h, right).

We kept the speed of stimuli consistent as in the *within-finger recognition* trial, but slightly altered the frame size to 2 × 3 [4] pins to create each directional movement (in a total of 4 frames). The total pins activated in each trial are shown in blue in Fig. 7 right. Note here, as mentioned previously, the speed of the stimuli is adjusted to 15mm/ms via the frame repeat time and frame-to-frame delay.

As with the previous experiment, we began with a five minute training session of each of the eight stimuli. In this case, all participants said that they felt confident after trying the stimuli for at most five times. The participants were then given each of the eight stimuli 12 times in random order (96 stimuli in total).

Again, participants were provided with printed sheets outlining the eight possible directional movements (Fig. 7 a–h) and were asked after each trial to select which one best matched what they felt. The overall recognition rate was then calculated based on the proportion of successfully matched trials.

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[4] This was because our technical evaluation concluded that 2 × 3 produced sharper stimuli at the corners compared to the 3×3 group.

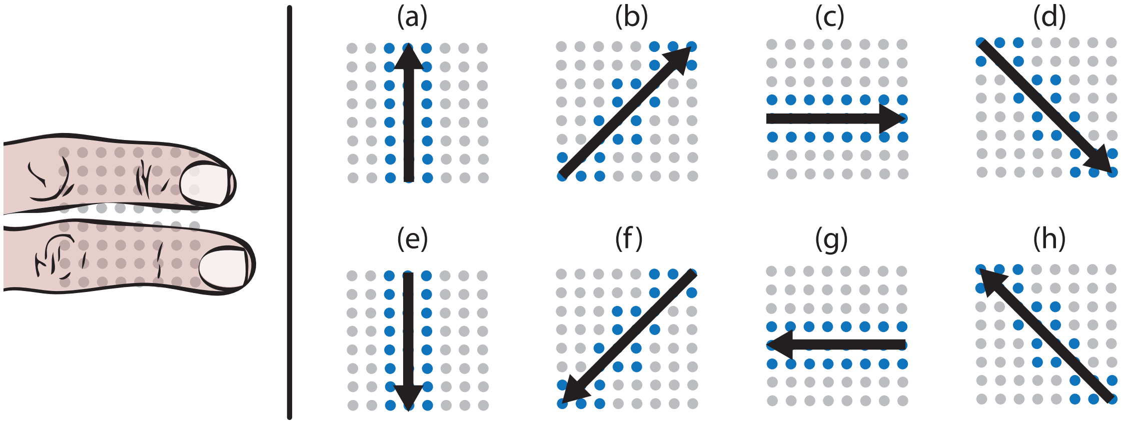

Fig. 7. Study 2: Inter-finger recognition. Left shows the finger placement used in Study 2, and right (a–h) shows the stimuli provided across each pair of fingers. Blue dots indicate the active pins used in each trial and the arrows show the direction of movement. Each movement was created by sequentially activating 2 × 3 blocks of pins along the direction of each arrow.

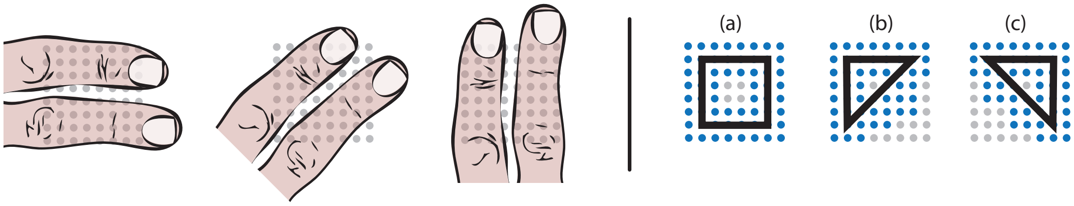

Fig. 8. Study 3: Grip orientation and pattern recognition. Left shows the finger placements used in Study 3, and Right (a–c) shows the stimuli provided. Blue dots indicate the active pins used in each trial and the shape shows the pattern. Each pattern was created by sequentially activating 3 × 3 blocks of pins along each shape.

5.2.3 Grip Orientation and Pattern Recognition. In this study, we were concerned with two factors: the effect of finger orientation and users' ability to detect patterns across fingers. The patterns are presented using (3 × 3) frames. They always start at the the finger tip of the index finger. This is to avoid the user guessing the patterns from the stimulus' starting point. For the square pattern and one of the triangle patterns (see Fig. 8 a and b), the block of pins were moving in a clockwise direction. In contrast, for the second triangle pattern (Fig. 8 c), the pin block moves anticlockwise.

To determine the effect of finger orientation, we conducted trials where the participant's hand was placed in three different positions (as shown in Fig. 8 left); horizontally (far left), vertically (far right) and at a 45 degree angle to the pin grid (middle). In this study we also evaluated the recognition rate of inter-finger shapes by 'drawing' simple shapes with the pins (Fig. 8 a, b and c).

In this study we opted for 3 × 3 groups of pins to create each shape (in a total of 4 frames)[5]. The speed was kept consistent at 15 mm/s as in Studies 1 and 2, and we again gave participants a choice of three potential printed images to choose from after each trial.

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[5] This was chosen from our trials of the prototype to give a better chance to feel the patterns when the grip (orientation of the fingers) was changed.

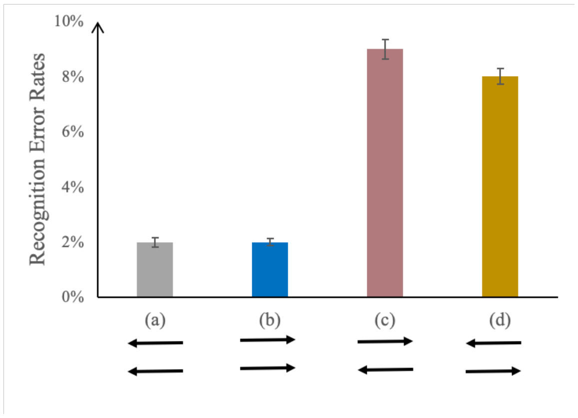

Fig. 9. Mean *Direction* recognition error rates for four directions (two in same and two in different directions). The error bars stand for one standard error about the mean.

After training with the different shapes and finger orientations, we proceeded to the study where each of the three patterned stimuli were activated a total of 30 times each (10 for each finger orientation) in a random order. The experiment was a 3 × 3 within-subjects design, where the independent variables were the pattern (which has three levels; see Fig. 7) and the finger orientation (which also has three levels; see Fig. 8). As with studies 1 and 2, we were interested in determining the recognition rate of the pattern.

5.3 Results

Of the 16 participants we originally recruited to take part in the experiment, 12 successfully passed the two point touch test. The results described below are of these 12 participants only. The remaining four had diminished sensitivity across all or part of their index and middle fingers, so did not partake in the remainder of the study.

5.3.1 Within-finger recognition. Figure 9 summarizes the recognition error rates of the different directional pairs of movements (as illustrated in Fig. 6 (a-d)). The overall recognition rate across the four pairs wa 95 %, with four participants achieving a 100 % recognition rate, and a further five making two or fewer mistakes.

To determine if the order of direction of the pairs of movements had an effect (i.e., if there is a difference in recognition between pairs going in the same direction, as in Fig. 6 (a) and (b), and pairs going in different directions, as in Fig. 6 (c) and (d)), we conducted an paired-samples t-test on the data. The results indicate a significant difference in the recognition rates for the *same* (M = .98, SD = .05) and *different* directions (M = .92, SD = .11); t (23) = 2.90, $p < 0.05$. That is, participants achieved a higher rate of recognition if both pairs of movements ran in the same direction.

A one-way repeated measures ANOVA was conducted to compare the effect of four types of direction combinations along both fingers (Fig. 6 (a), (b), (c) and (d)) on participants' recognition rates. There was no significant effect of direction types, F (3, 33) = 3.09, p = .06. This shows that among the four given stimuli (see Fig. 6) the participants' direction recognition rate within the finger remains at a reliably high rate.

The detailed breakdown of how participants made recognition mistakes is shown in Table 1, and indicates that participants were more likely to confuse one of the two *different* directional stimuli to the other (i.e., recognised (c) as (d) or vice versa).

Table 1. Confusion matrix for four directions.

Recognised direction		Presented direction			
		⇇	⇉	⇄	⇆
	⇇	93 %	1 %	2 %	4 %
	⇉	1 %	98 %	1 %	1 %
	⇄	0 %	1 %	96 %	3 %
	⇆	2 %	1 %	5 %	92 %

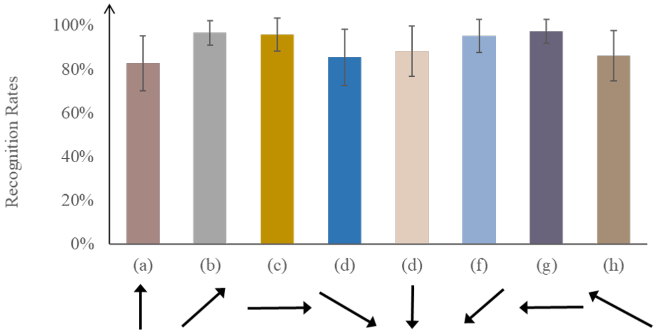

Fig. 10. Mean *Inter-finger* recognition rates for eight conditions. The Error bars stand for one standard error about the mean.

5.3.2 Inter-finger recognition. Figure 10 shows the recognition rates in each of the eight inter-finger conditions. The overall successful recognition rate was 91 %. A one-way repeated measures ANOVA found a main effect of the eight conditions (see Fig. 7), p < .001 (F (7, 77) = 4.67). Post-hoc tests showed that participants achieved a significantly higher recognition rate on conditions (b) (M = .97, SD = .13), (c) (M = .96, SD = .08), (f) (M = .95, SD = .07) and (g) (M = .97, SD = .05) compared to the remaining four conditions (a, d, e and h), all $p \leq .012$. This shows that the stimuli which crosses the middle and proximal phalanx of the middle finger caused more recognition confusion.

A detailed breakdown of how participants made mistakes is shown in Table 2. It indicates that most recognition confusions happen due to mistakenly recognising directional stimuli as being 45 degrees in a direction either side of itself (e.g., interpreting b (North Easterly direction) as a (North direction) or as c (Easterly direction), etc.). We can deduce from this that the main confusion is coming from directional stimuli that are closest together. However, we could potentially achieve a higher recognition accuracy if we considered the two similar directions as one.

5.3.3 Grip Orientation and Pattern Recognition. The recognition error rate of the three different patterns in each finger orientation are are shown in Fig. 11. A two-way repeated-measures ANOVA found no significant main effect of finger orientation, F (2, 22) = 2.56, p = .10 and pattern, F (2, 22) = 1.06, p = .36. They were also not qualified by a two-way interaction, F (4, 44) = .61, p = .06. We can deduce from this that the recognition rate on each pattern was reliable at 98% recognition across all three finger orientations, no matter how participant's position their fingers on the Active PinScreen.

Table 2. Confusion matrix for eight orientations.

Recognised direction \ Presented direction	↑	↗	→	↘	↓	↙	←	↖
↑	83 %	3 %	1 %	0 %	0 %	0 %	1 %	6 %
↗	9 %	97 %	0 %	0 %	0 %	0 %	0 %	1 %
→	0 %	1 %	96 %	7 %	1 %	0 %	0 %	0 %
↘	0 %	0 %	3 %	85 %	3 %	0 %	0 %	0 %
↓	1 %	0 %	0 %	7 %	88 %	3 %	0 %	0 %
↙	0 %	0 %	0 %	1 %	7 %	95 %	1 %	1 %
←	1 %	0 %	0 %	0 %	1 %	1 %	97 %	6 %
↖	6 %	0 %	0 %	0 %	0 %	0 %	1 %	86 %

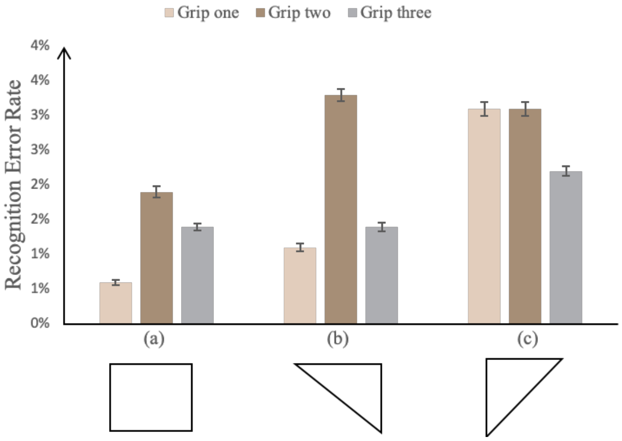

Fig. 11. Mean *Pattern* recognition error rates for three different pattern with three different position of the grip. The error bars stand for one standard error about the mean.

6 SUMMARY OF FINDINGS

The results of our lab evaluation show that participants who do not have diminished finger sensitivity are accurately able to detect a range of directional patterns using our Active PinScreen. The mean pattern recognition rates achieved were 95 % for *within-finger*, 91 % for *inter-finger* and 98 % for the three *grip orientations*. We also found that participants' perceptions were better for the movement of the same directions on two fingers (i.e., patterns (a) and (b) in Fig. 6) than different directions (i.e., patterns (c) and (d) in Fig. 6). Furthermore, participants demonstrated high recognition rates for patterns across finger tips (i.e., patterns (b), (c), (f) and (g) in Fig. 7). The three shapes that combined the *within-finger* and *inter-finger* patterns achieved relatively high recognition rates, and this was reliable even when changing grip orientation.

7 APPLICATIONS

Our work has focused on the difficult engineering task of miniaturising a haptic surface and evaluating user's ability to differentiate a range of patterns. However, the outcome of the studies suggests a number of potential applications for the device, if embedded on the back of a mobile device.

We envision that Active PinScreen devices could be useful in many mobile use-case scenarios. Some of these might be eyes-free: for example, providing directional cues in navigation via the sorts of patterns presented in Study 2; and, enriching haptic message notification by using different patterns—such as those seen in Study 3—for different message types.

Alternatively, we can imagine the use of the array as a means of enhancing eyes-on interfaces. To this end we built two game apps that used the device: Pacman and Running Car. The left/right and up/down swipes on the front screen of the Pacman game are reflected in within- and inter-finger stimuli at the back of the device. The car of the Running Car game can jump to avoid crashing into the other car by tapping on the front screen. The inter-finger stimuli at the back of the device mimic this jump action. Fig. 8 (a) and (e) show the pins' movements in this game (i.e., (a) when jumping up and (e) when down). Separately, we carried out an informal test of the game with six participants, and they were excited by the new technology and liked playing with realtime dynamic tactile feedback.

In the post-study interview, the participants commented that the Active PinScreen-based tactile feedback could be useful in playing video games and using apps that have a directional element such as shooting, racing, running, or walking. Customising these spatio-temporal patterns for personal notifications, gesture typing with tactile feedback, touch input confirmation, multi-modal digital content discovery, compass/sound-equaliser apps, and using the pins for relaxation/massage were also imagined by the participants.

In order to facilitate further research on the dynamic pin array and to enable application developers to include the output as part of their interfaces, a open-source toolkit is provided for others to implement and adapt our hardware/software approach [6].

8 IMPROVING THE PROTOTYPE'S OPERATION

Tailoring stimuli: In the post user study interview, the participants' average user experience rating of the stimuli using the 5-point scale on the strength was 3.42 and on the comfort was 3.75. Most users agreed that the stimuli of the Active PinScreen felt comfortable and the strength was medium. A few users commented that the strength of the stimuli was stronger near the index fingertip and reduced towards the base of the finger. However, we actuated the pins to apply a constant force. The strength of the stimuli perceived by the participants was a reflection of their sensitivity variations over the fingers. To provide a uniform sensation, the strength of the stimuli could be varied to match with the user's sensitivity variation, and the user could tune the stimuli themselves once per device with their preferred force, grip position and orientation.

Providing static sensations: We used a "push-type" linear solenoid actuator to provide sensation to the fingers. The base of each pin is physically trapped by the top-cover and typically retreats into its hollow casing due to gravity, recoil force from the top-cover, or by a finger press. The stroke length of the pins is ≈1 mm, and the stimuli were sufficiently felt at different orientations of the device. Users receive tactile feedback from the pins when they are pulsed, but they do not exert a static force, which would require wider pulses. This would lead to higher energy consumption, resulting in higher thermal dissipation and therefore a risk of burning the coils. The energy consumption could be

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[6] https://github.com/FITLab-Swansea/ActivePinScreen

reduced using the bistable electromagnetic latching method [34], giving a push-pull type actuator with which the pins would be able to reliably provide more force to the finger. However, it would require a more complicated H-bridge based driving circuits for each solenoid [42].

Adapting to the user's grip: An Active PinScreen device could integrate a sensor to facilitate user input and estimate the grip. Many technologies exist for input at the back of a mobile device [2, 20]. The touchscreen of a smartphone could be used to estimate the user's grip [19, 31], which could be integrated with the Active PinScreen without additional hardware to provide tailored tactile feedback at the back of a mobile device.

Dealing with a user's ability to sense stimuli: The sensitivity of fingers varies significantly from person to person. We performed the two-point discrimination test on all of the participants we invited to the study, and determined that a large proportion (25 %) had diminished sensitivity and were discounted from the study as a result. Specifically, we encountered two female participants who had diminished sensitivity on the intermediate and proximal phalanges despite having good sensitivity on the distal phalanx; they could not perceive the movement of the pins of study-1 along the length their index and middle fingers. We also encountered two male participants who had diminished sensitivity on their entire finger including the distal phalanx; they could only sense the pins moving along their finger with stimuli that we had evaluated as very strong. One way to address the limitation is to develop a calibration process for Active PinScreen devices to specifically tune it to particular users (as mentioned above) to provide stronger feedback where required.

Accommodating finger size differences: As with sensitivity, a person's finger size is also a variant which will affect how our prototype is used. For smaller or slimmer individuals, there would be some pins which can not be covered by two fingers, for example. One way to address this is to allow the user to customise/choose how many rows of pin which they prefer for the stimulation.

9 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented the Active PinScreen – a novel method of providing high-resolution tactile feedback to fingers on the back of a mobile device. Using an array of individually addressable, miniature, magnetic pins, we are able to provide spatio-temporal stimuli to provide directional and patterned feedback for users. Via technical and lab-based user evaluations, we discovered that with dynamic stimuli at 15 mm/s, users who do not have reduced finger sensitivity can recognise both within- and inter-finger directional and patterned simulations with up to a 98 % success-rate. As well as describing a detailed description of the technical components of the prototype, we also provided a discussion on alternative designs, application scenarios and areas for future research in the area.

The next step in our work in this area is to test the Active PinScreen in longitudinal deployments to assess its viability in real-world scenarios. This would require the further development of apps as well as refinement to the casing of the prototype (i.e., to make it smaller and custom fit to specific devices). We envisage that this technology could be integrated into cases that can be easily clipped onto any smartphone to add an extra layer of tactile feedback for users.

While we have considered mobile phone devices, larger arrays of Active PinScreens could also be developed to allow sensations on more than two fingers or even full palms. Different configurations could also be developed to suit different scenarios or devices (e.g., game controllers). The two-point discrimination test showed that some participants had low-sensitivity fingers. A study to assess whether the population possessing fingers with low-sensitivity shown in our test can be replicated, and what patterns are especially problematic among the low-sensitivity participants, will be conducted in the future.

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