PocketView: Through-Fabric Information Displays

Antony Albert Raj Irudayaraj
School of Computer Science,
University of Waterloo
aariruda@uwaterloo.ca

Rishav Agarwal
School of Computer Science,
University of Waterloo
rragarwal@uwaterloo.ca

Nikhita Joshi
School of Computer Science,
University of Waterloo
nvjoshi@uwaterloo.ca

Aakar Gupta
School of Computer Science,
University of Waterloo
aakarg@fb.com

Omid Abari
School of Computer Science,
University of Waterloo
omid.abari@uwaterloo.ca

Daniel Vogel
School of Computer Science,
University of Waterloo
dvogel@uwaterloo.ca

ABSTRACT

People often have to remove their phone from an inaccessible location like a pocket to view things like notifications and directions. We explore the idea of viewing such information through the fabric of a pocket using low resolution bright LED matrix displays. A survey confirms viewing information on inaccessible phones is desirable, and establishes types of pockets in garments worn by respondents and what objects are typically put in pockets. A technical evaluation validates that LED light can shine through many common garment fabrics. Based on these results, functional hardware prototypes are constructed to demonstrate different form factors of through-fabric display devices, such as a phone, wallet, a key fob, a pen, and earbud headphone case. A simple interaction vocabulary for viewing key information on these devices is described, and the social and technical aspects of the approach are discussed.

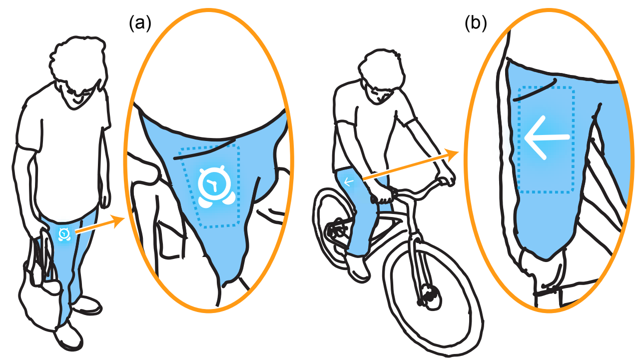

Figure 1: A through-fabric display for a pant pocket: (a) receiving a notification during encumbered walking; (b) viewing directions while bicycling.

CCS CONCEPTS

• **Human-centered computing** → **Displays and imagers**; *Mobile devices.*

KEYWORDS

mobile interaction; wearables; ubiquitous computing

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1 INTRODUCTION

Mobile phones are an indispensable part of daily life, and we carry them everywhere. But, accessing information on them is not always convenient. For example, when a phone is in a pocket and emits a sound or vibration to signal a new notification, the phone must be retrieved from the pocket to see the information. This retrieval process can be socially awkward during meetings, it can be cumbersome when carrying something in your hands, and it can be difficult, or dangerous, when walking or biking.

The question is, how can smartphone content be made visible, when the smartphone itself is stored in a pocket? Possible solutions include wearing a smartwatch, headphones, or augmented reality glasses to receive smartphone information. However, this introduces additional cost, technical complexity, requires additional visible accessories to be carried or worn by the user, which may not be suitable in all settings. Other more radical ideas could add a flexible LED display to clothing [24], or integrate displays directly into fabric using thermochromatic ink [6], E-ink [8], or woven optical fibres [22]. Instead of placing a display on fabric, or weaving a display into fabric, we explore how to make phone information visible *through* fabric, so it is always accessible even when the phone is stored inside a pocket. This could be used for applications like viewing notification types or turn-by-turn directions (Figure 1). A through-fabric device can complement other wearables as well. For example, viewing smartwatch information hidden under a sleeve or augmenting a headphone-based audio interface with additional visual information.

We conduct a small preliminary survey followed by a more extensive main survey to understand different types of pockets in clothing, the objects stored in them, and the need to access information when the phone is inaccessible. We find that for almost

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all participants (>90%), irrespective of age and gender, phones are the most popular object stored in various types of pockets. Men prefer storing phones in pockets located in the lower body area while women prefer the stomach area. We then conduct a technical experiment to validate the ability of an LED matrix to shine through common fabrics. The results show that LED pixels can shine through common fabrics, while light transmission is affected by fabric thickness, knit, and weave type, and irregularity is affected by patterns such as checkered designs. Motivated by the survey and technical experiment, we designed an initial through-fabric display prototype using a matrix of bright LEDs that users can place in their pocket and interact with using simple knock gestures. We evaluated the prototype in a 12-person user study to validate the general approach, including a baseline using a standard phone display with bright, high-contrast imagery and a futuristic pocket that can be made transparent on demand using Polymer Dispersed Liquid Crystal (PDLC) film. Our results show the feasibility of the concept, with participants favouring the LED matrix for comfort. Comments about the futuristic PDLC pocket approach show there is a desire for selectively viewing information through a pocket in terms of usability, ease of interaction, visibility, and amount of information. We built different form factors using LED matrices that can attach to an earbuds case, pen, and keyfob. Using multiple, smaller objects makes through-fabric displays more inclusive to objects commonly stored in smaller pockets, typically found in women's clothing [7]. We contribute, what we believe, is the first investigation into creating a through-fabric pocket display. These wearable displays are a hybrid between smart textiles, ambient displays, and traditional wearable devices like a smartwatch.

2 RELATED WORK

Our work relates to smart textiles, on-body displays, "see-through" displays, and interaction through pockets.

2.1 Smart Textiles

Smart textiles are used for instrumenting clothing for input. For instance, garment fabrics can be augmented with iron-on sensors, as in Klamka et al. [21] and Polysense [16], or even sewn or woven into garment fabrics, like conductive threads in Project Jacquard [30] and Pinstripe [20], electrospun nanofiber-based materials [3], and others for detecting moisture [41] or pressure in RESi [27]. A common goal of smart textile input is to control a smartphone, but the output remains tied to the phone. A through-fabric display complements these input methods by providing an method for integrating a display into clothing.

More relevant to our work, is past research on using smart textiles as displays. One approach is thermochromic textiles that use heating elements to change colour, and create displays using the fabric itself [28, 38]. For example, Ebb [6] demonstrates how thermochromic yarn can be woven to create a low-resolution, non-emissive textile display and Ambikraf [29] animates patterns on common fabric with the help of thermochromic inks and peltier semiconductor elements. Using thermochromic textiles enables fashionable, clothing-like aesthetics, but they are very slow to change, and tend to be more suitable for ambient information. Methods like Optical Fiber Displays [22] aim to spin optical fibres directly into clothing to serve as flexible displays. However, Braunder et al. [2] survey the broader area of interactive smart textiles and conclude that there is a lack of reliable conductive yarns technologies and they can currently be used for demonstration purposes only.

2.2 On-body Displays

Apart from smart textiles, researchers have also integrated LED or E-ink based displays on clothing. For instance, Mauriello et al. [24] use LED-based displays fixed to the back of a shirt or jacket to display fitness statistics and Colley et al. [5] integrated RGB LED strips into shoes to help runners visualize their pace. Grosse et al. [11] studied suitable locations to wear display and built LED display prototypes for the arm and back. When worn, they can indicate turn and stop signals while biking. Similarly, Idle stripe shirt [13] uses fibre-optic threads to generate display patterns. Online fashion brands like LED Clothing sell clothes and shoes with integrated LED lights for fashion and costumes [1]. AlterNail [9] and AlterWear [8] are small, simple, and minimal E-ink displays that can be integrated into clothing like hats, shoes, and shirts. AlterWear is battery-free and relies on NFCs for powering and communication, however, fabrics still need to be instrumented to accommodate these devices.

Schneegass et al. [33] explore on-body displays to extend the display area of a smartwatch using low-resolution LED matrix. They describe a prototype using a 16×8 LED matrix that shines through white t-shirt fabric, but the goal is to simulate low resolution garment based displays, not explore its through-fabric nature. Their focus is on finding suitable locations for on-body displays, visualization methods, and the efficacy of visualizing off-screen data in a navigation task. In contrast, we focus on the motivation and potential of a pocket-based through-fabric display, including light transmission capabilities, device form factors, and usability.

2.3 See-through Displays

A transparent material can enable access to a display in a stored location. Colley et al. [4] create a transparent slot in a hand bag to view a tablet display. They explore how this can be used to customize the bag colour for fashion, to view and interact with objects stored inside the bag (including a mobile phone), and as a social display with a personal message. Sugiura et al. [34] create a wrist worn prototype for simultaneously showing private and public information. The system uses a sandwich of retro-reflective material and electronically controllable PDLC film with a head-worn projector for content. The PDLC film rapidly switches between an opaque state, in which projected content is visible to nearby people, and a transparent state where the retro-reflective material makes private projected content only visible only to the user.

We use PDLC film to create a switchable version of Colley et al.'s slot in the form of an instrumented pant pocket. Unlike shining light through fabric, a PDLC pocket requires the garment to be specially modified, making it less practical. However, in our usability study, it provides an extreme baseline for upper limits of the through fabric approach since it enables a standard phone display to be easily viewed inside a pocket.

2.4 Interaction On and Around Pockets

Previous work has explored using front pant pockets, and the upper thigh in general, for sensing input. Thomas et al. [36] found using a mouse on the front thigh is most favoured by participants when sitting, kneeling, or standing. Smart pockets [37] uses pocket-based gestures (e.g., placing hands in a certain pocket) as input for a large ambient display. PocketThumb [10] is a touch interface integrated into a pocket to control wearable like AR glasses. PocketTouch [32] investigates the practicality of adding touch input into a pocket, or through the fabric of a pocket. The results suggest that using a specially modified capacitive sensor, smartphone touch input could work while in a pocket, through many fabrics. Ronkainen et al. [31] and Hudson et al. [17] explored using tapping (or "whacking") gestures as input for mobile devices. We also adopt this simple method to interact with a phone when in a pocket, but a through-fabric display could be extended to use more advanced input methods like PocketThumb [10] or PocketTouch [32].

3 PRELIMINARY SURVEY

We conducted a short preliminary survey to establish if there is a need to access information when a phone is inaccessible and to begin to understand phone storage preferences in different scenarios. The online survey had 10 questions about phone storage when walking or in a meeting, frequency of accessing phone information, and the need to access information when hands are occupied[1]. There were 106 respondents, ages 17 to 68 (79 male, 23 female, 1 genderfluid, 2 did not answer).

The results show that respondents generally want to access information on their phones in different scenarios. When walking, 28.3% indicated they wanted to access information on their phones every 1 to 6 minutes, and 35.8% every 6 to 20 minutes. When asked about the importance of accessing information on their phones when their hands were occupied, 37.7% indicated high importance (4 or more on a 5 point scale). These results show that many people want to access information on their phone, even when it may not be convenient to do so. In response to where respondents kept their phones in different scenarios, relatively few women used their pant pockets. While walking, 97.4% of the male respondents stored their phones in their pant pockets, whereas only 30.4% of the female respondents do the same. Similarly, during a meeting, most male respondents (57%) kept their phones in their pant pocket, but most female respondents (69.6%) kept it on a desk or table.

Overall, men commonly store their phone in pant pockets, but women less so. Two related studies, one interviewing people on the street [18] and the other semi-structured interviews and an online survey [40], also found men predominantly store phones in their pant pockets, while women prefer shoulder bags or purses. They note phone storage location is affected by societal perceptions of gender, culture, and age, as well as physical constraints due to pocket size and clothing. For example, women's clothing typically has smaller pockets [7].

While our preliminary survey motivates a need for accessing information from an inaccessible phone in different scenarios, the survey design was limited in terms of understanding phone storage preferences and gender diversity. The questions only asked about storing a phone in a limited range of clothing pockets (pant, shirt, and coat pockets), which women may not use, let alone wear, frequently. But there are many other clothing pockets of varying sizes and on different parts of the body that could be leveraged to create more inclusive through-fabric displays. Likewise, asking only about storing a phone in a pocket may be too limiting. There are other smaller objects that people place in pockets, like keys and credit cards, that could be augmented as well.

4 MAIN SURVEY

We conducted a extensive follow-up survey to understand whether people wear clothing with pockets, where pockets are located, and the types of objects stored in each pocket. Results from the survey are also used to understand the effect of gender on the pocket location and stored objects. In addition, this survey confirms the preliminary survey result showing a need to access information on an inaccessible phone, and expands this to include what alternative methods respondents are using now in that situation.

4.1 Protocol

The survey was conducted online, and disseminated to the general public through social media. There was no remuneration. It had three main sections with 39 questions total[2]. The first section asked respondents about pocket locations on clothing they typically wear and what kinds of items they store in different pockets. These questions used illustrations of representative types of clothing, such as pants, jackets, and skirts, to convey pocket locations. The second section asked respondents about the importance, frequency, and methods for accessing information on their phone when it is inaccessible, like when in a pocket. The third section asked about demographics like age and gender. Respondents were told to consider their behaviour both during and before the COVID-19 pandemic.

4.2 Results

There were 112 people who completed the survey. The respondent sample has reasonable gender balance, with 57 identifying as male, 52 as female, 1 non-binary, and 2 did not answer. 93 respondents provided their age. They spanned 19 to 71 years, but are skewed slightly younger overall with 68% between 19 to 35 years, 22% between 35 to 50 years, and the remaining 10% 50 or older. Although our survey was distributed internationally, we did not record the geographic location or climate of where our respondents live. We believe indoor garments are reasonably consistent across regions and cultures, but our sample may not adequately capture all clothing types (such as winter parkas).

Table 1: Percentage of respondents who wear clothing with eight pocket locations.

	Female	Male	Overall
Upper Thigh	96.2	98.2	95.5
Back of Leg	92.3	94.7	92.0
Stomach	90.4	80.7	83.9
Lower Thigh	40.4	35.1	36.6
Chest Area	36.5	66.7	51.8
Waist/Waistband	30.8	1.8	15.2
Arm	17.3	10.5	13.4
Back	0	0	0

4.2.1 Clothing Pocket Locations.

The survey asked participants whether they wore clothing with pockets in any of 8 body locations: on the chest area (e.g., dress shirt); on the arm (e.g., sleeve pocket); near the stomach (e.g., front hoodie pocket); on the waist/waistband

[1] The full preliminary survey is provided as supplementary material.

[2] The full main survey is provided as supplementary material.

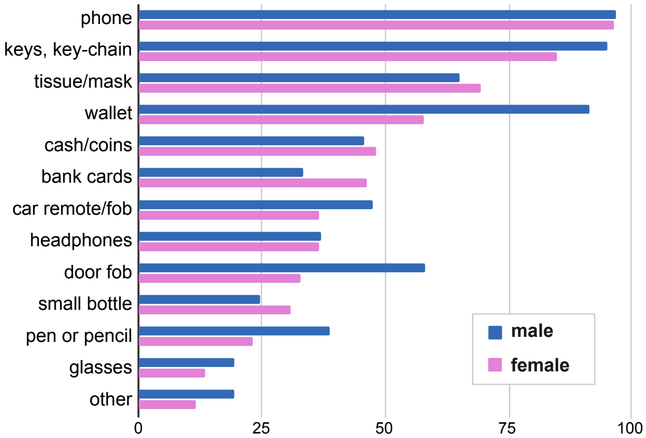


Figure 2: Types of items stored in pockets by gender (x-axis is % of respondents).

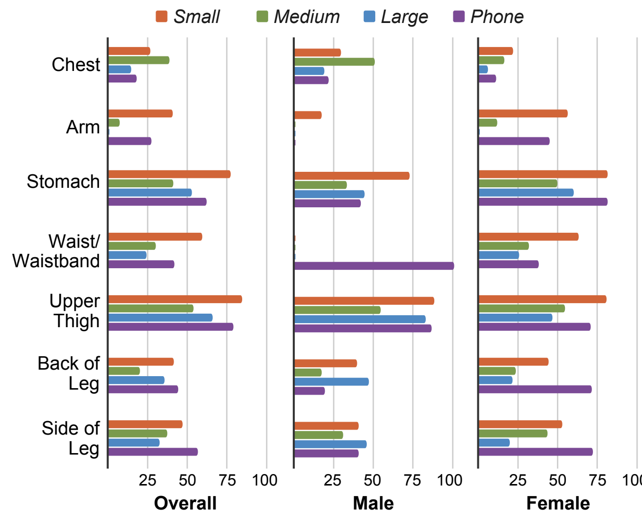


Figure 3: Pocket locations where phones and three sizes of items are stored overall, and by gender. The x-axis shows the conditional percentage of respondents who both answered they wear garments with pockets in a given area and that they store one or more items in that pocket. The back is excluded as no respondents indicated they wore clothing with pockets in this area.

(e.g., waist pockets on leggings/workout shorts); on the front upper thigh (e.g., front jean pocket); on the back of the leg (e.g., back jean pocket); on the side of the leg (e.g., side pockets on cargo pants); and on the back (e.g., back of a sports bra).

Responses indicate that participants wear clothing with pockets located on the upper thigh area (95.5%) and the back of the leg (92%). Clothing with pockets on the arm (13.4%) and back (0%) were least-commonly worn. Among our respondents, women wore more clothing with pockets on the stomach (90.4% F, 80.7% M) and waist areas (30.8% F, 1.8% M). Men wore more clothing with pockets in the chest area (36.5% F, 66.7% M).

4.2.2 Items Stored in Pockets. If the participants indicated that they wore clothing with pockets on the specified location, the survey asked them to select the types of objects stored in these types of pockets. Possible answers were nothing, or choosing one or more options from a list of 12 common types of items: phone; wallet; keys or key-chain; door fob; car fob/remote; loose bank cards; loose cash/coins; headphones and/or case; pen or pencil; glasses; tissue or face mask; or small bottle (e.g., hand sanitizer). An open text "other" option was also provided.

Overall, when considering the objects kept in any pockets, phones were most popular (94.6%), with other popular items being keys/key chains (88.4%), wallets (74.1%), and tissue/face masks (65.2%). For most objects, men and women reported similar storage preferences; for example, both men and women placed their phones in a pocket (on any location of the body) > 96% of the time. However, a higher proportion of men placed wallets in pockets than women (57.7% F, 91.2% M), but women were more likely to place loose bank cards in their pockets than men (46.2% F, 33.3% M). Men were more likely to store pens/pencils in their pockets than women (23.1% F, 38.6% M), as well as door fobs (32.7% F, 57.9% M) (Figure 2).

To examine the specific objects placed in each pocket location, we first group the types of items into four categories by size for reporting purposes: "phone"; "large" for headphones/headphone case, wallets, and glasses; "medium" for bank cards, car remote/fob, pen or pencil, small bottle; and "small" for door fob, keys/key-chain, cash/coins, tissue/mask. We calculate the percentage of respondents that store a group of objects in a specific pocket location. Note that these percentages are the percentages of total respondents who reported wearing clothing with pockets at the indicated pocket location, rather than the percentage of all respondents. For instance, if the respondent did not report wearing clothing with arm pockets, they were not asked to indicate the types of objects they stored in arm pockets. Overall, people stored many different objects of varying size in different pockets (Figure 3). Respondents stored objects of all groups in every pocket type, with the exception of storing large objects in arm pockets. The upper thigh area is the only pocket location where the majority of respondents stored objects of all groups (all > 53%), and is the most common location for small objects (84.1%) and phones (78.5%). However, men were more likely to store large objects (46% F, 82.1% M) and phones (70% F, 85.7% M) in upper thigh pockets than women, who store small objects in these pockets instead. Women also tended to use a wider range of pocket locations to store objects; for example, they stored a wider variety of objects in arm and waist pockets than men (only 1 male respondent reported wearing clothing with pockets on the waist). Phone storage was spread across more pocket locations for women. With the exception of the single male respondent who reported using a waist pocket, men primarily relied on upper thigh pockets to store their phones, but women stored their phones in pockets located at the side of the leg, back of the leg, upper thigh, and stomach area (all ≥ 70%). The stomach area in particular, was the most common location for storing a phone for women and was more commonly-used than men (80.9% F, 41.3% M).

4.2.3 Accessing Information on an Inaccessible Phone. The survey asked a series of questions to understand the need and methods for accessing information on an inaccessible phone. In response to the question, "are there ever times where you cannot access your phone even though you wish to", a majority, 67.8%, responded yes and 40.1% felt that their ability to access their phones is moderately to extremely important.

A series of questions also asked how respondents currently access information normally viewed on a phone. Only 28.6% of our respondents wore a smartwatch and among those, 56.7% used it "about half the time" or more to access information on their phones. 29.1% of our respondents used a voice assistant "about half the time" or more to do the same. Among other devices, 93.7% participants use a laptop to access information they would typically view on phones, but this of course is only possible in a non-mobile context.

4.3 Discussion and Implications

These results validate the general idea of making information on inaccessible phones more accessible. Although a smartwatch or audio-based virtual assistant can fill this need, our survey suggests these methods are not frequently used. Our results also show phones are often kept in the various on-body pockets of both men and women. Most men placed their phones in the thigh area but more women used pockets in the stomach area for their phones. This confirms that our preliminary survey was limited in terms of understanding where women store their phone since it did not cover a comprehensive range of possible pocket locations. We use these results to motivate our initial design of a smartphone case through-fabric display for an initial prototype and usability test.

It is important to recognize the pocket used to hold a phone differs for women. This could be due to smaller front pockets in women's jeans and pants, making them hard to fit even medium sized-phones [7]. Our results do show that women place a phone in other front pockets that would be visible, but also that the back pocket is commonly used, a location which would make a personal through-fabric display on the phone case less practical.

However, we also find a large diversity of other items kept in pockets, including medium and large sized objects that would have enough surface area for a through-fabric display and internal space for necessary electronics. Importantly, we find that many of these items are kept in pockets that would be visible to the individual. We explore the idea of augmenting other objects like wallets, car remotes, headphone cases, and pens to create working through-fabric prototypes in Section 6. Before we describe any prototypes, we first report on an experiment that answers another set of fundamental questions about how LED light shines through fabric.

5 LIGHT TRANSMISSION EXPERIMENT

This section describes a technical experiment to validate and understand the ability of a LED matrix display to shine through common garment fabrics. Prior work has studied light transmission through fabrics to understand characteristics relevant to normal applications, such as curtains that block light or how sheer fabric may not work well for clothing. Relevant to our work are the general approaches and how both light sensors and image processing used as measurement methods. Past work examining light transmission through knitted fabrics [19] and curtains [23, 35] used a lux sensor or light intensity meter. Some approaches process images captured from a camera to compute light transmission, such as an investigation of 40 different weave types [25] and polyester and cotton blends [12]. We use a camera to capture images of different light patterns shining through a fabric sample and also measure light illumination with a lux sensor. Using the images, we compute light transmission and irregularity values which are indicative of the optical properties of a through-fabric display in a garment.

5.1 Apparatus

A 3D printed rectangular frame was designed to hold a 8×8 RGB LED matrix (Adafruit 1487) measuring 71×71 mm. Each LED in the matrix operates at 300mW, all powered by a single 5V, 4 amp source. These LEDs are sufficiently bright to shine through a wide range of fabrics, and it represents a best case scenario for our tests. We trigger each LED as a binary "pixel", either completely turned off or as a white pixel operating at maximum brightness setting.

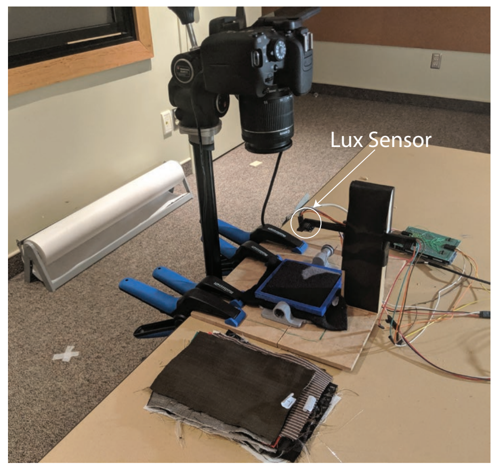


Figure 4: Fabric light transmission apparatus: each fabric sample is placed over an LED matrix display housed in plastic frame and a DSLR camera and light sensor are used for measurements. A lux sensor is used as a baseline for light measurements using the camera.

Each fabric sample is firmly secured to the display using a square hoop (Figure 4). A Canon Rebel T5i DSLR camera captures images of the LED patterns shining through the fabric sample. The camera view direction is co-linear with the fabric sample normal, with the camera 21 cm away from the fabric surface. A Rohm BH1750 digital light "lux" sensor is also placed 11 cm above the fabric to measure light intensity reflecting from, or shining through the fabric in lux. The lux sensor provided a relative baseline for light transmission values measured using the camera. The camera measures light at different positions of the fabric, which makes measures for patterned and irregular fabrics more reliable, and this is critical when measuring irregularity across individual LEDs. The images are captured inside a dark room, and the camera is set in manual mode with a 1/100 second shutter speed (TV=100), f10 aperture (AV=10), and 400 ISO. These values are chosen as the upper threshold in which no light enters the camera when the LED matrix is turned off. The images are captured with a resolution of 1728×2592 pixels and stored as a 24-bit JPG file. These images are cropped to extract the region within the rectangular hoop and then processed to calculate different metrics. A desktop C# application is interfaced with an Arduino Mega to control the LED matrix and to issue commands to the camera to capture images with specific settings.

5.2 Fabric Samples

Clothing fabrics are composed of one or more types of raw material fibres which are combined together using a manufacturing process. Fibre material is classified as natural (e.g. cotton), synthetic (e.g. polyester), or mixed fibre[3] (when fibre content is unknown and cannot be accurately determined). Manufacturing process is primarily categorized as woven (e.g. denim) or knitted (e.g. barcelona knit). We worked with an experienced salesperson at a large textile retail store to select a range of representative fabric samples that are typically used for garments.

The raw materials used for fibres in our samples include two natural types: Cotton (C) and Ramie (RA); six synthetic types: Polyester (P), Rayon (R), Spandex (S), Metallic Fiber (MF), Polypropylene (PLP), Nylon (N); as well as Mixed Fibre (MIF) types.

The manufacturing processes used to combine fibres in our samples include ten woven types: Flannel (FA), Satin (S), Denim (D), Chiffon (CF), Poplin Prints (PP), Velvet (V), Metallic Jacquard (MJ), Georgette (G), Plaid (PL), and a generic weave (W); five knitted types: French Terry (FT), Kluffy Knits (KK), Lorie Lace (LL), Fleece (FL), Barcelona Knits (BK), and Tuscany Knits (TK); and a spunbond type (SB). Note some manufacturing processes use proprietary names.

In the results that follow, each fabric sample is labelled with an ID using the raw material and manufacturing process codes above, as well as the mm thickness in parenthesis. For example, a fabric with ID 'D-C (0.59)' corresponds to a denim manufacturing process with cotton fibres with thickness 0.59mm and 'W-CPS (0.67)' corresponds to a woven fabric with fibres composed of cotton, polyester, and spandex with thickness 0.67mm. Each fabric sample is cut into 20×15cm swatches to fit over the image capture frame.

5.3 Results

This section discusses the quantitative findings from the experiment in terms of light transmission and irregularity.

5.3.1 Light Transmission. Light transmission measures the amount of light that passes through the fabric. To calculate our relative light transmission measure, we first capture a reference image with matrix turned on without any fabric sample on top. This is used with binary thresholding to find regions of interest for each LED pixel, and the intensity at each pixel is used to normalize light transmission measures. Then, each fabric sample is placed over the LED matrix and an image is captured with all the LED pixels turned on. Using the region of interest, transmittance is calculated as the ratio between sum of grayscale pixel intensity with the fabric to the sum of grayscale pixel intensity without the fabric.

Due to the reference image normalization, our transmittance measure ranges from 0 to 1: '0' implies that the fabric completely blocks out the light and '1' implies that the fabric completely allows light to pass through the fabric. Transmission values near to '0' would be more visible in the dark room but not in sunlight, values from 0.3 to 0.6 would be visible in a well-light room, and values greater than 0.8 will be visible even in sunlight. Transmittance values of 1.01 is likely due to sensor noise in bright images and suggests an estimated measurement precision of ±.01. The lux values correlate with our transmission metric, and they provide an absolute measure of overall light transmission.

Table 2 shows the light transmission values for the different fabric samples. Transmittance is high for very thin fabrics like 'CF-P (0.2)' and 'KK-MIF (0.39)', and very low for thicker and darker fabrics like velvet 'V-C (0.72)' and thick denim cotton fabrics 'D-C (0.67)', 'D-C (0.92)', and 'D-C (1.02)'. Barcelona Knit fabric 'BK-PS (0.4)' is thin, but light transmission is affected due to its knitting type. We expected waterproof fabrics to have low transmission, but for the two Nylon waterproof fabrics we tested, 'W-N (0.19)' and 'W-N (0.13)', one has very high full transmission and even the other has a lower, but still usable 0.21 transmission.

5.3.2 Irregularity. Irregularity measures how evenly light is transmitted through different areas of a fabric. Specifically, it is the standard deviation of light transmission for 16 individual LEDs that span the area of the display. This is computed by capturing a fixed sequence of 16 images, each with only a single LED illuminated. Similar to light transmission, reference images are used to obtain the region of interest (ROI) around each LED. The mean grayscale pixel intensity is calculated for the illuminated LED ROI in each of the 16 images. Irregularity is then the standard deviation of these 16 mean intensity values.

Table 2 shows the irregularity values. The irregularity value is low for fabrics that can shine light evenly across the fabric and vice versa. Irregularity is high for fabrics with dyed designs, textures or patterns, and low for solid fabrics without any texture on it. Fabrics with design or patterns tend to have higher regularity values because of the uneven light distribution across the fabric sample. Fleece Polyester fabric 'FL-P (0.94)' is dyed with an image of bear and poplin prints 'PP-C (0.2)' has a design with contrasting black and white regions increasing the regularity value because of the patterns on the fabric. The checkered pattern on fabrics 'FA-C (0.49)' and 'MJ-PS (0.57)' also increases their irregularity values. For fabrics with design or patterns, the irregularity could also vary based on the location of the fabric sample on the LED matrix.

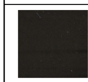
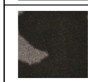
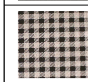
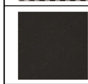
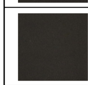
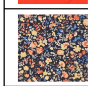
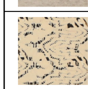
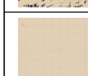
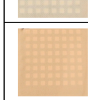
5.4 Discussion

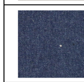
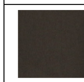
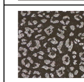
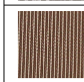
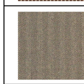
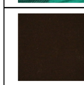
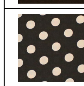
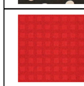
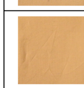
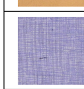
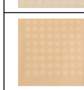
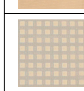
The experiment validates the ability of an LED matrix to shine through certain garment fabrics. Light transmission is affected by fabric thickness, knit type, weave type, and material. Regularity is affected in fabrics with patterning, dyed images, and checkered designs. These metrics help in understanding the feasibility, limitations, and design consideration for a through-fabric display. It is important to acknowledge that not all fabrics will work, thicker and darker fabrics generally have lower transmission levels. Overall, these results show that many types of garment fabrics transmit enough light generated by an LED matrix to be visible for a user.

5.4.1 Visual Separability. Visual separability of the light pattern transmitted through fabric is an another factor that affects the usefulness of through-fabric displays. This measure would capture how well people could distinguish individual pixels in different patterns, which is likely affected by different types of weaves,

[3]"mixed fiber" is a standard term, e.g.: https://www.competitionbureau.gc.ca/eic/site/cb-bc.nsf/eng/01544.html

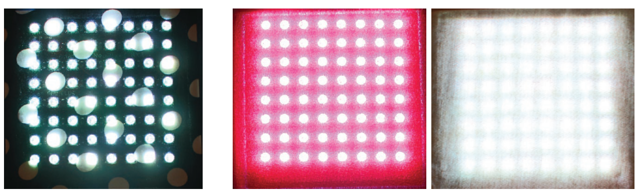
Table 2: Fabric experiment results for Transmittance, Irregularity, and Lux

	Fabric (thickness mm)	**Trans**	**Irreg**	**Lux**
	'BK-PS (0.4)'	0.0	0.54	0
	'D-C (0.67)'	0.0	0.73	0
	'D-C (0.92)'	0.05	3.48	1
	'D-C (1.02)'	0.09	9.07	3
	'FA-C (0.5)'	0.21	12.76	16
	'FL-P (0.94)'	0.28	49.73	14
	'MJ-PS (0.57)'	0.32	36.38	46
	'W-C (0.3)'	0.48	12.81	53
	'W-P (0.21)'	0.62	5.0	65
	'D-C (0.59)'	0.66	8.98	76
	'W-CS (0.23)'	0.85	2.99	640
	'PP-C (0.19)'	0.89	7.89	466
	'W-C (0.25)'	0.94	2.68	884
	'FT-CS (0.66)'	0.95	3.29	290
	'KK-MIF (0.39)'	1.0	0.26	650
	'LL-MIF (0.58)'	1.0	0.03	2332
	'D-C (0.58)'	1.01	0.0	1614
	'W-RA (0.27)'	1.01	0.0	2150
	'SB-PLP (0.37)'	1.01	0.0	3046
	'TK-RS (0.53)'	1.01	0.0	2495

	Fabric (thickness mm)	**Trans**	**Irreg**	**Lux**
	'W-CPS (0.67)'	0.0	0.18	0
	'V-C (0.72)'	0.01	2.8	0
	'W-P (0.43)'	0.08	4.7	3
	'D-C (0.88)'	0.14	5.88	5
	'W-N (0.13)'	0.21	5.56	10
	'MJ-PRMF (0.29)'	0.31	6.59	20
	'PL-MIF (0.44)'	0.36	3.0	49
	'PL-PR (0.44)'	0.51	9.26	49
	'FA-C (0.49)'	0.64	38.88	90
	'TK-RS (0.38)'	0.72	8.88	165
	'PP-C (0.2)'	0.85	14.06	550
	'G-P (0.38)'	0.9	3.65	564
	'W-C (0.53)'	0.94	0.61	280
	'W-CS (0.35)'	0.97	0.85	363
	'W-C (0.27)'	1.0	0.08	713
	'S-P (0.21)'	1.01	0.01	1759
	'W-C (0.25)'	1.01	0.01	2375
	'W-N (0.19)'	1.01	0.01	2178
	'CF-P (0.2)'	1.01	0.02	3509
	'W-CP (0.37)'	1.01	0.01	1271

interaction with fabric patterns and material blends, and adherence of the fabric to the LED matrix. For example, the high contrast, high frequency floral pattern of the Poplin Print fabric sample ‘PP-C (0.2)’ affects separability because the LED pattern visually interacts with the fabric pattern, causing some LED pixels to appear to merge, creating “bridging” patterns (Figure 5a).

Separability is affected by the distance from the LEDs to the fabric. When the LEDs are not tight against the fabric, the resulting gap increases diffusion making the through fabric display blurrier (examples in Figure 5b,c). This effect is most prominent in thicker fabrics. This is not a pronounced problem with more tailored or form-fitting clothing or when a device in a pocket naturally lays against the pocket fabric. To mitigate this issue, an internal clip or magnet can hold a LED through-fabric display tightly against the inside of the pocket fabric.



(a) (b) (c)

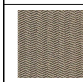
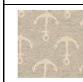
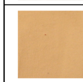
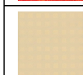
Figure 5: Visual separability examples: (a) bridging patterns in a polka dot fabric ‘PP-C (0.2)’; diffusion effect when fabric is placed 2mm above the LED matrix for (b) thin fabric ‘G-P (0.38)’; (b) thick fabric ‘W-C (0.53)’.

We tested several possible objective quantitative measures for separability, but were not able to find one that was repeatable and represented the subjective experience of a person interpreting a through fabric display pattern. We note that many contemporary clothing fabrics have little or no high contrast patterns, so in practice this may not be a common issue.

5.4.2 Multilayered Fabrics. Another consideration is that light transmission may be affected by multiple fabric layers. For example, pockets are often lined with a thin cotton material like ‘W-C (0.25)’. Although we did not test fabric in layers, given the high transmittance of this type of fabric, we believe it will have little effect on light transmission when used as an inner lining. Some garments use multiple layers of thick fabric, such as a formal suit jacket or winter jacket. We plan to test these more extreme examples in the future, but note that even with these garments, there are typically some external pockets that have a single or minimal layers of fabric, for example, a shirt or a hoodie pocket.

5.4.3 Light Colour and Other LED Matrices. This experiment tested the white light output of a single model of high power LED matrix with a wide range of fabrics to validate the general approach. In supplementary materials, we provide results when red, green, and blue components of the captured images are analyzed separately. There is no pronounced change in the metrics with our fabric samples, but an in-depth examination of the interaction of light colour and fabric dye colour is an interesting topic for future work.

Table 3: Transmittance for other display sources (results from Table 2 for the “bright 8×8 LED matrix” used in main experiment provided for comparison).

Fabric (thickness mm)		**Phone**	**8×8 matrix**	**15×7 matrix**	**from Table 2**
	‘D-C (0.88)’	0.0	0.02	0.03	0.14
	‘PL-PR (0.44)’	0.0	0.14	0.22	0.51
	‘FT-CS (0.66)’	0.01	0.43	0.6	0.95
	‘W-C (0.53)’	0.02	0.43	0.68	0.94
	‘W-C (0.25)’	0.1	0.47	0.71	0.94
	‘S-P (0.21)’	0.16	0.93	1.01	1.01

It is also informative to compare these results with other types of through-fabric displays. We measured transmittance for a standard phone (Google Pixel 2, P-OLED display) displaying high contrast pixels at maximum brightness, a smaller 1.2×1.2 inch 8×8 LED matrix (Adafruit 1614), and a 2×0.9 inch Charlieplex Feather Wing 15×7 LED matrix (Adafruit 3163). We calculated light transmission similar to the main experiment on a sub-sample of six fabrics chosen to cover a range of transmittance with the high power LED matrix. The results are shown in Table 3. The phone screen image is visible through some fabrics, but transmittance is much lower and becomes too low to be visible with thicker fabrics. The 15×7 matrix has slightly better transmittance than the 8×8 matrix. The bright LED matrix used in the main experiment has very high transmission values compared to all the matrices and phone, thus making it suitable to design through-fabric displays that can work on a wider range of fabrics. These results validate the ability of other variations of LED matrices to shine through fabrics, while a standard phone can only work through thin fabrics.

6 POCKETVIEW DEVICE PROTOTYPE

Motivated by the surveys and technical evaluation results, we created a hardware and system design with a simple interaction vocabulary for a through-fabric display device suitable for a pocket. We use available electronic components to create our novel device. This initial prototype is used in the user study that follows, after which variations on this first prototype are presented to demonstrate additional form factors and interaction design variations.

6.1 Hardware and System

A RGBW Neopixel 8x8 display (Adafruit 2872) is mounted on a custom PCB and controlled by an Arduino promini micro-controller (Figure 6a). The prototype board measures 115×71×15mm and can be enclosed inside a 121×77×18mm 3D printed case (Figure 6b).

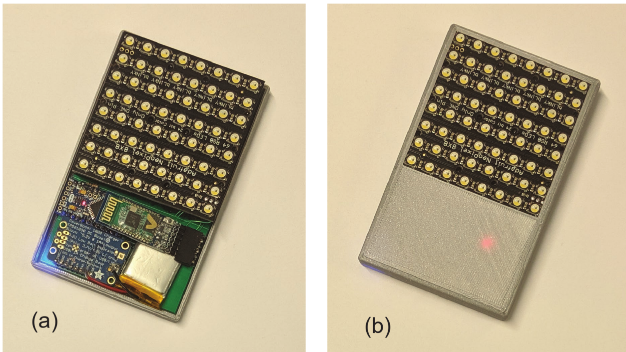


Figure 6: Device prototype: (a) self contained battery-powered, wireless device with 8×8 LED display; (b) as assembled in a 3D printed case with a phone-sized form factor.

A HC-05 bluetooth module communicates with the smartphone to receive content to be displayed on the LED matrix. The entire system is powered using a 3.7V, 420mAh Lithium battery and can be recharged using a USB power supply. Each LED (SK6812) has a maximum current rating of 60 mA. As an approximate estimate of run time, we considered typical usage with occasional notifications and temporary information. We model this power consumption as half the LEDs illuminated for 5 seconds every 5 minutes, and calculate the prototype would run for 2 hours.

The form factor of this prototype can represent a through-fabric display housed in a custom phone case, or as a stand-alone device carried in the front pocket resembling a wallet (with the phone placed in a back pocket or bag). Our single-sided prototypes must be inserted into a pocket with the LED matrix facing out to work as a display. This also provides an explicit way to silence or hide a through-fabric display by simply changing the orientation. The Android app sends a bit stream required to display appropriate imagery on the matrix display. This would enable an Android app to sync with other apps like health, email, and calendar to display appropriate through-fabric content.

6.2 Interaction Vocabulary and Applications

We designed simple graphic icons to convey information related to weather conditions, arrows for navigation directions, and various types of notifications, like a message or a reminder (Figure 7). A set of numerals in a similar graphic style is used for quantitative information like calories burnt, time left before the next meeting, and fitness tracking. Low-resolution icons are displayed on the standard phone and LED case prototype. Interaction uses single taps on the pocket [17, 31], to cycle through different information sources (like weather to navigation to fitness and back to weather). Double taps dismiss notifications after they arrive, or turn off the display. The tap gestures are intended to provide simple, quick (and ideally subtle) interaction while viewing the information displayed through the pocket. For simplicity, our initial prototype is placed over the phone like a phone case, and the built-in microphone of the smartphone is used to detect single and double taps.

7 USER STUDY

The goal of this qualitative user study is to test our initial through-fabric prototype in a simulated usage setting to validate the general approach of the hardware, interaction design, and potential usage scenarios. For a relative comparison, we include two baselines.

7.1 Baselines

The baselines serve as extremes in through-fabric device approaches.

7.1.1 Standard Phone. This baseline approach uses a standard phone display to shine information through fabric (Figure 8a). The screen is set to maximum brightness and uses high-contrast 8×8 pixelated white-on-black imagery approximating the fidelity of the LCD matrix display. This approach is simple and immediately applicable, but limited to shining through light coloured, thin fabrics, in low ambient light conditions. The built-in phone sensors are used to detect single and double taps for interaction.

7.1.2 PDLC Transparent Pocket. This baseline is a radical approach which imagines future fabrics that can dynamically change from opaque to transparent. The intention is to provide participants with a device example that could enable "perfect" through-fabric viewing. The device is a "window" of Polymer Dispersed Liquid Crystal (PDLC) film over a phone-sized hole cut out of a front pant-pocket (Figure 8b). This film can switch between opaque and transparent states by controlling the current passed through the film. Otherwise, the condition is the same as the phone baseline.

7.2 Protocol

We recruited 12 participants ages 22 to 31 (1 female, 11 male) from a university student population. Based on a short questionnaire, 10 stored their phone in a pant pocket, the others used a backpack and coat-pocket. With one female participant, this study is limited in terms of generalizing to women.

During the session, the participant used all three through-fabric device conditions, one at a time: the standard phone baseline; the PocketView LED phone case prototype device; and the PDLC transparent pocket. They were provided with light, white-coloured pants for the first two prototypes, and blue jeans fitted with the PDLC prototype. Most chose to wear the supplied loose-fitting pants over their existing clothes. The experimenter used a desktop application to trigger notification events on the smartphone and LED matrix display. A custom android app running on the smartphone, received these commands from the experimenter's application, and rendered the corresponding icon to the screen, or interfaced with the micro-controller to render it on the LED matrix.

While wearing each prototype, the participant was asked to stand, sit in a chair, and sit on a bicycle. They then used the prototype interaction vocabulary to view different information sources with single taps, and the experimenter sent notification alerts at random times, which the participant dismissed with a double-tap. During this time, they were prompted to "think out loud" to externalize their thoughts and experiences for observation [26]. After trying all three device conditions, they ranked each for visibility, comfort, usefulness, ease-of-interaction. They also provided an overall preference for each device using a 5-point numeric scale. After, a semi-structured interview was conducted. Interviews were

Figure 7: Interaction vocabulary imagery demonstrated with different kinds of clothing and pockets: (a) numeral 5 through cotton pants; (b) fitness icon through knit dress; (c) mail notification icon through hoodie; (d) message notification icon through front pocket of lycra tights.

conducted following best practices [39], and all but two were audio recorded (due to a technical error). Each session lasted approximately 30 minutes.

7.3 Results

In terms of overall preference, 91.7% assigned scores of 4 or higher for the LED matrix and 83.4% for the PDLC transparent pocket. Meanwhile only 66.7% assigned a score of 4 or higher to the standard phone baseline. Participants ranked all three prototypes similarly in terms of ease-of-interaction. From rankings, think-aloud observations, and interviews, there were six themes that emerged.

Phone Visibility — The standard phone baseline was ranked the lowest on visibility. Participants expressed skepticism on its utility outdoors, *"not sure how usable it is in sunlight"* [P12]. Meanwhile, most users preferred the LED prototype owing to its high visibility, though one participant thought it might be *"too loud"* [P12]. Another participant wondered whether a *"[standard phone and LED phone case] would not work with absolutely all types of fabric"* [P1]. We expected participants to comment on the viewing angle when standing, sitting, or when on the bicycle, but no one specifically commented on viewing angle as an issue.

Use in Different Scenarios — 7 participants indicated that they often need to access information on their phone while their hands are occupied. While walking with hands are encumbered, 6 participants preferred the PDLC pocket and 5 preferred the LED case. In meeting scenarios, 9 participants preferred having a display so that they would not miss out on importation notifications while having their phones on silent, for example *"a visual indication would be better in environments where phone has to be kept on silent"* [P5]. One participant also mentioned the general convenience of being able to view through the pocket, *"sometimes it's difficult to take out the phone when you're sitting and so this can be useful even when my hands are free"* [P3].

Figure 8: User study baseline device conditions: (a) a standard phone with high contrast pixelated imagery; (b) a futuristic PDLC transparent pocket to make a standard phone display completely visible "through fabric".

Use for Different Tasks — Regardless of though-fabric device, participants imagined several tasks such as controlling music, reading messages, or navigating using Maps being done directly from the pocket. *"nice to have phone in the pocket while running"* [P7]. *"Having Maps here is the most interesting feature"* [P11]. One participant said that *"even though it divides my attention but it would be really useful if I can interact with the phone on the bike and answer calls"* [P2]. Another wished to *"have special pockets like this for the gym"* [P8] where they could workout without having to take the phone out of their pockets.

Less Reliance on Third Party Devices — Participants commented on reducing the reliability on third party devices for accessing information. One participant mentioned that *"headphones do it somewhat but [controlling music] is better if you can do it directly from your phone"* [P1]. Participants also commented on how all approaches obviate the need for information to be synced, *"I can use it [PDLC] with any kind of phone without worrying about iOS, Android compatibility or Bluetooth syncing"* [P11]. However, in practice, this only really applies to a standard phone. A transparent pocket technology like PDLC would need a connection to the phone to synchronize transparency with display events on the phone. The same is true for the PocketView device, it needs a wireless connection with the phone to receive image rendering patterns. In both cases, these connections only need to support real time output events, not synchronizing data stores which adds additional considerations for security and privacy.

Managing Privacy — Several participants raised concerns related to privacy, for example *"I would not use this if it showed too much information in public"* [P3]. In particular, some feared the PDLC might

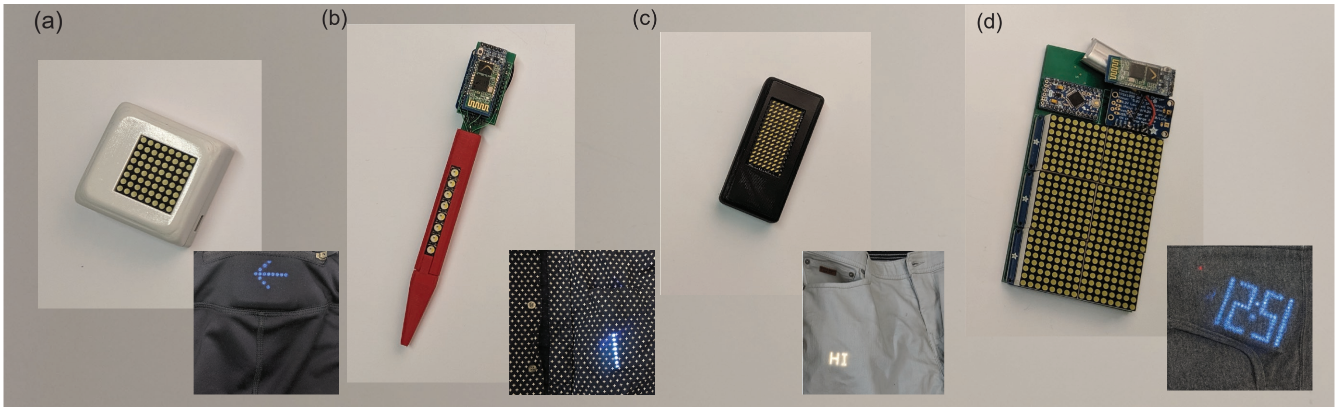


Figure 9: Prototypes showing form factor variations: (a) earbud headphone case; (b) pen; (c) car remote; (d) phone case.

accidentally become transparent and show too much information: *"I would not like to use a transparent pocket in a social setting"* [P5]; and *"I would not use this [PDLC] when someone is walking towards me, for example, my prof and I'm getting a lot of messages."* [P11]

Fashion and Aesthetics — While people did not complain about the aesthetics of the LED matrix prototype, they did not find the PDLC prototype to be visually pleasing. One participant said that *"only issue is how it looks and feels"* [P4], and several participants mentioned that being fashionable is very important.

7.4 Discussion

Overall people preferred the LED prototype in terms of managing privacy and fashion aesthetics. While the PDLC approach was able to provide more information, some users were comfortable with the minimal information provided with the LED device, given that it allowed multitasking and reduced the reliability on other third party devices like a smartwatch. There was also a positive reception to the "through-fabric" aspects of the PDLC. We interpret this as a validation of the general concept of a through-fabric display. This prototype has clear practical limitations: PDLC does not feel or flex like fabric given its stiff and plastic properties, even full opacity is quite transmissive compared to a fabric like denim. However, as one baseline in our study, it was effective for helping participants make a relative comparison between a "perfect" through-fabric pocket display in terms of transparency and image fidelity.

8 DESIGN VARIATIONS AND LIMITATIONS

In this section, we present other device form factor variations and discuss limitations and considerations for the general approach.

8.1 Device Variations

To demonstrate how the PocketView through-fabric display concept can be extended, we built different prototypes resembling other items that might be stored in a pocket. Like our initial prototype, all but the car remote prototypes are self-contained with a microcontroller (Arduino Pro mini), Bluetooth chip (HC-05), lithium-ion battery, and Powerboost 1000C (Adafruit 2465) module for boosting and USB battery charging. The car remote prototype has all components except a Bluetooth chip. These form factors demonstrate different use cases of through-fabric devices, and they are informed by the results of our main survey showing the diversity of garment pockets and what kinds of objects are placed in pockets.

Earbuds Headphone Case — We built a prototype resembling a headphone earbuds case (Figure 9a). It would be small enough to fit in many different pockets, most notably the front pocket of women's jeans. It contains a small 1.2×1.2 inch 8×8 square LED matrix interfaced to a driver circuit (Adafruit 1614) all enclosed in a $62 \times 60 \times 28$mm 3D printed case with rounded corners. It is powered using a 250mAh lithium-ion battery.

Pen — We also explored a small prototype with a restricted display in the form factor of a pen (Figure 9b). A linear 8×1 LED strip (Adafruit 2869) is mounted on a custom PCB. The LED strip and on-board circuitry are powered from a 110mAh battery. The LED strip is enclosed in 3D printed case resembling a pen, which measures $121 \times 14 \times 11$mm. Most electronics remain external to the case which simplified this demonstration prototype development. The low resolution one-dimensional display necessitates a simplified version of the interaction vocabulary. Numeric values, such as for fitness counters or meeting timers, can be shown as a bar along the strip. Different notification types can be conveyed using patterns and animations.

Car Remote — A car remote (or "car key fob") is another convenient form factor for a PocketView device (Figure 9c). Our prototype uses a Charlieplex Feather Wing 15×7 LED matrix (Adafruit 3163). It measures $76 \times 34 \times 17$mm and its small form factor can also fit into a wide range of pocket sizes.

Phone Case — We also experimented with a higher resolution display prototype in a phone case form factor (Figure 9d). It uses six 8×8 LED matrices along with a driver board (Adafruit 2308) tiled together to form a 24×16 through-fabric display. It uses the same LED matrix as the earbuds case. All the components are mounted on a custom PCB and measures $138 \times 74 \times 17$mm. This prototype can display information like scrolling text, for example a grocery shopping list or more details about a specific notification, like an email or text.

8.2 Applications

Even with a simple interaction vocabulary and low resolution display, PocketView through-fabric displays can show notifications, reminders, track progress of an activity, or act as social displays. Different form factors will be suitable for different pocket locations, sizes, and usage scenarios.

Notification Assistant — When inserted in a front pant pocket, navigation instructions can be shown while walking or biking, or it can act as signal indicators when inserted in a back pocket while cycling [11]. Users can also manually tap on the system to view weather updates or time before the next meeting when their phone is inaccessible to retrieve.

Fitness Tracking — Prototypes placed in a pocket of athletic wear can show fitness statistics like step count, calories burnt, heart rate, or track fitness goals while jogging, walking, or working out. Pen prototypes can visualize progress towards a goal as a bar plot, or the higher-res phone case prototype can show the fitness stats with more detail.

Social Displays — A prototype placed in a back pocket, for example, a sports bra back pocket, could function as social or public display [24]. The wallet prototype placed in the pant back pocket can display a social message or can trigger emergency medical notification to indicate the public of potential medical emergency. These displays can act as digital ID cards at conference when placed inside a neck wallet pocket.

8.3 Limitations and Design Considerations

We discuss current device implementation limitations and privacy implications for a personal through-fabric display.

Power consumption — The LED matrix display in the original prototype can consume up to 20 watts with all pixels illuminated. In practice, the display would be used for short periods to convey information at certain moments, and it can be made run at reduced power consumption with proportional reduction in brightness. For example, by intelligently reducing brightness based on the ambient lighting conditions and fabric transmission properties.

Prototype Size — Although we attempted to make the prototypes small, they remain slightly bulky because they are built using commercially available components. With more engineering, they can be made lighter and sleeker to more closely resemble different items, or even integrate with those items. For example, Apple iPhone "Magsafe" is a magnetic accessory attachment method with power and communication that could support a PocketView through-fabric display on a phone.

Privacy — We also note the privacy aspects of a through-fabric device like PocketView. Unlike third party devices like smart watches or voice assistants, our device has no capacity to store, share, or analyze any data. While the minimal information that is displayed can be seen by other people, it can be configured to convey no more than what a glowing phone or smartwatch notification would show. We can also imagine users might create custom obfuscated imagery that are uninterpretable by others.

Display Location — The location of a wearable display affects visual accessibility, interaction subtlety, and social acceptance. Harrison et al. [15] studied reaction times to visual notifications generated by LED nodes placed on different parts of the body. Wrist and shoe locations had the fastest and slowest reaction times respectively as participants predominantly spent time in a seated position. In another study, Harrison et al. [14] examined suitable locations to project content for on-body interfaces when standing or sitting. Arm and hands were most suitable, but notably, the thigh area received positive feedback for a seated posture. Some areas of the body are not socially acceptable for displaying content, and these positions can vary by gender. For example, women may be less comfortable with a display placed on the chest than men. Body shape influences visual accessibility. For example, people with a larger hip size may have more difficulty viewing content displayed on the lower body. Our PocketView prototypes are suitable for diverse wearable display locations, which may alleviate and compensate for the guidelines and issues above. Future studies can examine suitable locations and social acceptability.

Challenges with Cold Weather Outerwear — Our results show a general trend of lower light transmission with thicker fabric. This poses a limitation for using a through fabric display in the pocket of insulated clothing like winter parkas. In some cases, these garments have thin-walled outer pockets that are sewn on the outer wall of the jacket, which could be used.

9 CONCLUSION

We investigated how to create an unencumbered, always-accessible display for smartphone content through a pocket, a concept we call through-fabric displays An online survey explored different pocket location in garments, the items stored in them, and the need to access information when the phone is inaccessible. To explore the feasibility of through-fabric displays, we performed a technical experiment to validate the ability of a LED matrix to shine through common garment fabrics. Motivated by these results, we built a preliminary prototype for a through-fabric display using a 8×8 RGBW LED matrix in a phone-sized form factor. Then, a qualitative study conducted with 12 participants suggest the approach can be useful, and the general device form factor is reasonable. Finally, we show that these ideas can be generalized to other items typically stored in a pocket, like a pen, headphone earbud case, and car remote. Beyond creating a new type of wearable, our through-fabric devices could be used for prototyping smart textile interactions where the ultimate goal is to embed or weave a display into fabric.

We hope our work opens up a new space for designing interactions with smart devices without having to remove them from their stored location.

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REFERENCES

[1] 2019. Premium Handmade LED Clothing. (2019). http://led-clothing.com/
[2] Philipp Brauner, Julia van Heek, Anne Kathrin Schaar, Martina Ziefle, Nur Al-huda Hamdan, Lukas Ossmann, Florian Heller, Jan Borchers, Klaus Scheulen, Thomas Gries, Hannah Kraft, Hannes Fromm, Marina Franke, Christian Wentz, Manfred Wagner, Manuel Dicke, Christian Möllering, and Franz Adenau. 2017. Towards Accepted Smart Interactive Textiles. In *HCI in Business, Government and Organizations. Interacting with Information Systems*, Fiona Fui-Hoon Nah and Chuan-Hoo Tan (Eds.). Springer International Publishing, Cham, 279–298.
[3] Amutha Chinnappan, Chinnappan Baskar, Shikha Baskar, Greeshma Ratheesh, and Seeram Ramakrishna. 2017. An overview of electrospun nanofibers and their

application in energy storage, sensors and wearable/flexible electronics. *Journal of Materials Chemistry C* 5, 48 (2017), 12657–12673.

[4] Ashley Colley, Minna Pakanen, Saara Koskinen, Kirsi Mikkonen, and Jonna Häkkilä. 2016. Smart Handbag as a Wearable Public Display - Exploring Concepts and User Perceptions. In *Proceedings of the 7th Augmented Human International Conference 2016* (Geneva, Switzerland) *(AH '16)*. Association for Computing Machinery, New York, NY, USA, Article 7, 8 pages. https://doi.org/10.1145/2875194.2875212

[5] Ashley Colley, Paweł W. Woundefinedniak, Francisco Kiss, and Jonna Häkkilä. 2018. Shoe Integrated Displays: A Prototype Sports Shoe Display and Design Space. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction* (Oslo, Norway) *(NordiCHI '18)*. Association for Computing Machinery, New York, NY, USA, 39–46. https://doi.org/10.1145/3240167.3240216

[6] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. I don't want to wear a screen: probing perceptions of and possibilities for dynamic displays on clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 6028–6039.

[7] Jan Diehm and Amber Thomas. 2018. Women's Pockets are Inferior. *The Pudding* (Aug 2018). https://pudding.cool/2018/08/pockets/

[8] Christine Dierk, Molly Jane Pearce Nicholas, and Eric Paulos. 2018. AlterWear: battery-free wearable displays for opportunistic interactions. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 220.

[9] Christine Dierk, Tomás Vega Gálvez, and Eric Paulos. 2017. Alternail: Ambient, batteryless, stateful, dynamic displays at your fingertips. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 6754–6759.

[10] David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. 2017. PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 2 (2017), 9.

[11] Tobias Grosse-Puppendahl, Oskar Bechtold, Lukas Strassel, David Jakob, Andreas Braun, and Arjan Kuijper. 2015. Enhancing Traffic Safety with Wearable Low-Resolution Displays. In *Proceedings of the 2nd International Workshop on Sensor-Based Activity Recognition and Interaction* (Rostock, Germany) *(iWOAR '15)*. Association for Computing Machinery, New York, NY, USA, Article 10, 10 pages. https://doi.org/10.1145/2790044.2790059

[12] Noman Haleem, Sayed Ibrahim, Tanveer Hussain, Abdul Jabbar, Mumtaz Hassan Malik, and Zulfiqar Ali Malik. 2014. Determining the light transmission of woven fabrics through different measurement methods and its correlation with air permeability. *Journal of Engineered Fibers and Fabrics* 9, 4 (2014), 155892501400900409.

[13] Emmi Harjuniemi, Ashley Colley, Piia Rytilahti, Hong Li, Jesse Forest, and Jonna Häkkilä. 2018. Idle stripes shirt: ambient wearable display for activity tracking. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ACM, 254–259.

[14] Chris Harrison and Haakon Faste. 2014. Implications of Location and Touch for On-Body Projected Interfaces. In *Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver, BC, Canada) *(DIS '14)*. Association for Computing Machinery, New York, NY, USA, 543–552. https://doi.org/10.1145/2598510.2598587

[15] Chris Harrison, Brian Y. Lim, Aubrey Shick, and Scott E. Hudson. 2009. *Where to Locate Wearable Displays? Reaction Time Performance of Visual Alerts from Tip to Toe*. Association for Computing Machinery, New York, NY, USA, 941–944. https://doi.org/10.1145/1518701.1518845

[16] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.

[17] Scott E Hudson, Chris Harrison, Beverly L Harrison, and Anthony LaMarca. 2010. Whack gestures: inexact and inattentive interaction with mobile devices. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*. ACM, 109–112.

[18] F. Ichikawa, J. Chipchase, and R. Grignani. 2005. Where's The Phone? A Study of Mobile Phone Location in Public Spaces. In *2005 2nd Asia Pacific Conference on Mobile Technology, Applications and Systems*. 1–8. https://doi.org/10.1109/MTAS.2005.243793

[19] Manoj Kumar Imrith, Roshan Unmar, and Satyadev Rosunee. 2016. Investigating the relationship between knitted fabric porosity and light permeability. *Indian Journal of Materials Science* 2016 (2016).

[20] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: eyes-free continuous input on interactive clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1313–1322.

[21] Konstantin Klamka, Raimund Dachselt, and Jürgen Steimle. 2020. Rapid Iron-On User Interfaces: Hands-on Fabrication of Interactive Textile Prototypes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.

[22] Vladan Koncar. 2005. Optical Fiber Fabric Displays. *Opt. Photon. News* 16, 4 (Apr 2005), 40–44. http://www.osa-opn.org/abstract.cfm?URI=opn-16-4-40

[23] S Suresh Kumar, Vinay Kumar Midha, Alpa Kumari, Upma Gupta, and Shruti Singla. 2018. Transmittance behaviour of curtain fabrics under natural lighting conditions. (2018).

[24] Matthew Mauriello, Michael Gubbels, and Jon E Froehlich. 2014. Social fabric fitness: the design and evaluation of wearable E-textile displays to support group running. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2833–2842.

[25] Jiri Militky, Marie Travnickova, and Vladimir Bajzik. 1999. Air permeability and light transmission of weaves. *International journal of clothing science and technology* (1999).

[26] Gary M Olson, Susan A Duffy, and Robert L Mack. 2018. Thinking-Out-Loud as a Method for Studying 11 Real-Time Comprehension Processes. *New methods in reading comprehension research* (2018), 253.

[27] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, et al. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *The 31st Annual ACM Symposium on User Interface Software and Technology*. ACM, 745–756.

[28] Roshan Lalintha Peiris, Owen Noel Newton Fernando, Chua Su Bee, Adrian David Cheok, Arij Glycin Ganesan, and Prabhash Kumarasinghe. 2011. dMarkers: ubiquitous dynamic makers for augmented reality. In *Proceedings of the 10th International Conference on Virtual Reality Continuum and Its Applications in Industry*. ACM, 217–224.

[29] Roshan Lalintha Peiris, Mili John Tharakan, Adrian David Cheok, and Owen Noel Newton. 2011. AmbiKraf: a ubiquitous non-emissive color changing fabric display. In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*. 320–322.

[30] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. ACM, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[31] Sami Ronkainen, Jonna Häkkilä, Saana Kaleva, Ashley Colley, and Jukka Linjama. 2007. Tap input as an embedded interaction method for mobile devices. In *Proceedings of the 1st international conference on Tangible and embedded interaction*. ACM, 263–270.

[32] T Scott Saponas, Chris Harrison, and Hrvoje Benko. 2011. PocketTouch: through-fabric capacitive touch input. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 303–308.

[33] Stefan Schneegass, Sophie Ogando, and Florian Alt. 2016. Using On-Body Displays for Extending the Output of Wearable Devices. In *Proceedings of the 5th ACM International Symposium on Pervasive Displays* (Oulu, Finland) *(PerDis '16)*. Association for Computing Machinery, New York, NY, USA, 67–74. https://doi.org/10.1145/2914920.2915021

[34] Yuta Sugiura, Toby Chong, Wataru Kawai, and Bruce H. Thomas. 2018. Public/Private Interactive Wearable Projection Display. In *Proceedings of the 16th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry* (Tokyo, Japan) *(VRCAI '18)*. Association for Computing Machinery, New York, NY, USA, Article 10, 6 pages. https://doi.org/10.1145/3284398.3284415

[35] Joanna Szmyt and Zbigniew Mikolajczyk. 2010. Light transmission through decorative knitted fabrics in correlation with their fabric cover. *AUTEX Research Journal* 10, 2 (2010), 44–48.

[36] B Thomas, Karen Grimmer, J Zucco, and Steve Milanese. 2002. Where does the mouse go? An investigation into the placement of a body-attached touchpad mouse for wearable computers. *Personal and Ubiquitous computing* 6, 2 (2002), 97–112.

[37] Radu-Daniel Vatavu. 2017. Smart-Pockets: Body-deictic gestures for fast access to personal data during ambient interactions. *International Journal of Human-Computer Studies* 103 (2017), 1–21.

[38] Akira Wakita and Midori Shibutani. 2006. Mosaic textile: wearable ambient display with non-emissive color-changing modules. In *Proceedings of the 2006 ACM SIGCHI international conference on Advances in computer entertainment technology*. ACM, 48.

[39] Robert S Weiss. 1995. *Learning from strangers: The art and method of qualitative interview studies*. Simon and Schuster.

[40] Jason Wiese, T. Scott Saponas, and A.J. Bernheim Brush. 2013. *Phoneprioception: Enabling Mobile Phones to Infer Where They Are Kept*. Association for Computing Machinery, New York, NY, USA, 2157–2166. https://doi-org.proxy.lib.uwaterloo.ca/10.1145/2470654.2481296

[41] Shuai Xu, Qian Ma, Xiao-Fang Yang, and Shu-Dong Wang. 2017. Design and fabrication of a flexible woven smart fabric based highly sensitive sensor for conductive liquid leakage detection. *RSC Advances* 7, 65 (2017), 41117–41126.