AlterWear: Battery-Free Wearable Displays for Opportunistic Interactions

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Figure 1. Three AlterWear prototypes. Note how well the technology is integrated into the garments. Left: Tee shirt pocket display (i.e. pattern). Middle: Segmented hat display (i.e. stars). Right: Discreet sneaker display (i.e. Catverse logo). AlterWear couples energy harvested from an NFC-enabled device with e-ink displays to afford dynamic interactions and expressions without the need for on-board power.

ABSTRACT

As the landscape of wearable devices continues to expand, power remains a major issue for adoption, usability, and miniaturization. Users are faced with an increasing number of personal devices to manage, charge, and care for. In this work, we argue that power constraints limit the design space of wearable devices. We present AlterWear: an architecture for new wearable devices that implement a batteryless design using electromagnetic induction via NFC and bistable e-ink displays. Although these displays are active only when in proximity to an NFC-enabled device, this unique combination of hardware enables both quick, dynamic and long-term interactions with persistent visual displays. We demonstrate new wearables enabled through AlterWear with dynamic, fashion-forward, and expressive displays across several form factors, and evaluate them in a user study. By forgoing the need for onboard power, AlterWear expands the ecosystem of functional and fashionable wearable technologies.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

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Author Keywords

wearables; cosmetic computing; ambient displays; e-ink displays.

INTRODUCTION

As wearable devices continue to proliferate throughout culture and society, the available form factors are increasingly diverse in terms of size and physical location on the body. This new wave of wearable technology includes smart textiles [20, 21], tattoos [14, 10], fingernails [9, 23, 27], makeup [26, 28, 11], and beyond [8]. However, many of these wearable devices retain the need for some source of on-board power, therefore requiring the user to charge, swap batteries, and otherwise maintain. In this paper, we focus on a specific class of wearables that do not need to be charged, cared for, or even removed — AlterWear. By explicitly designing around these particular constraints, we identify a set of unique interactions.

AlterWear

AlterWear combines NFC and e-ink technologies to enable battery-free, dynamic wearable displays. These displays can be incorporated into a number of different form factors, and fuse interaction, information, and fashion while remaining lightweight and low maintenance.

Each AlterWear device has a visible e-ink display. This display may be discreet and only noticeable to the user themselves, or it may be outward-facing and public. In either case, this display is powered and updated when it comes in contact with near-field communication (NFC). This increasingly ubiquitous wireless power source is commonly found in mobile phones, IoT devices, and public infrastructure. AlterWear leverages

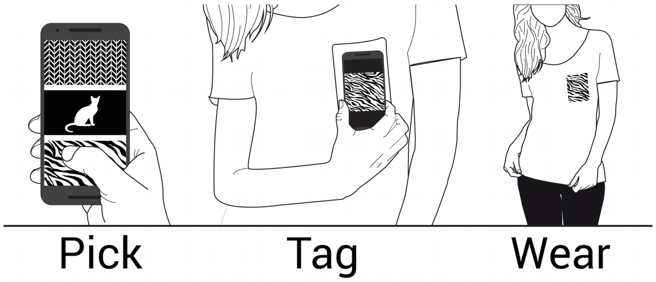

Figure 2. Interaction model for AlterWear displays. Users 1) pick a design using their Smartphone or other NFC-enabled device, 2) tag the device to their display to update it, and then 3) wear their new design without the need to recharge it, update it, or maintain it.

this synergistic infrastructure to opportunistically power and update e-ink displays. The bistable nature of these displays allows designs to persist for long periods of time without additional power or maintenance. Persistent contact with NFC also allows for animated dynamic displays. We argue that our presented architecture can enable a diverse range of new wearable devices and can enable intentionally performative and playful interactions. While not inherently cosmetic in nature, we believe that AlterWear can inspire and inform the creation of *Cosmetic Computing* form factors [4].

RELATED WORK

Prior work has addressed the issue of power in wearable systems. Some new wearables resolve power constraints by leveraging chemical interactions rather than electrical ones [12, 15]. Other work has harvested energy from human motion [13], public landscapes [18], personal objects [19], and radio frequencies [17, 25]. Another way to address limited power resources is to lower power requirements. Prior work has leveraged the bi-stable, low-power nature of e-ink displays in battery-free devices that use photovoltaic energy [5] or wireless power [4, 2, 32]. AlterWear contributes to this body of work by presenting a diverse array of wearable form factors that require no battery, yet have a persistent bistable display, and leverage the increasing ubiquity of wireless power.

Our work is also related to prior work on situated displays that argues that information is more meaningful when displayed in contextually relevant locations [5, 29, 16]. In addition to designing contextually, many researchers and designers alike have also opted towards ambient, ambiguous, and abstract displays [3, 7]. AlterWear expands this body of work by presenting additional form factors for displays that are subtle, intentionally unobtrusive, and often ambiguous in meaning. We also contribute to the expanding understanding of users' perceptions of wearable displays, synthesize findings from a user evaluation, and present design guidelines for creating battery-free wearable displays.

MOTIVATION

The number of commercial wearable devices is constantly expanding to include new functionalities, form factors, and affordances. These wearable devices aim to make life easier by tracking fitness and health, improving connectedness and communication, and simply entertaining the user. While many devices are effective to this end, wearable devices impose an additional responsibility on users to charge, care for, and

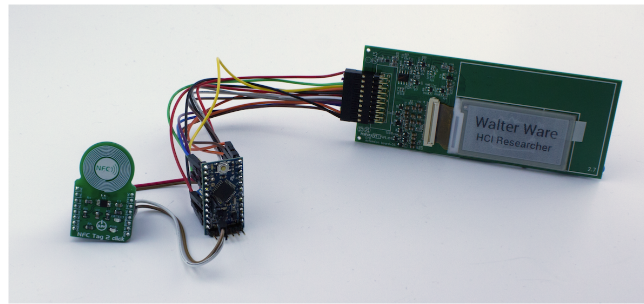

Figure 3. Our larger prototypes use an NFC Tag 2 Click breakout board, an Arduino Pro Mini microcontroller, and an e-ink display with EPD Extension Kit. While these components are relatively large and bulky, the size can be significantly reduced with custom hardware (see Figure 8).

maintain. Wearable devices also often demand attention with persistent updates and notifications. Research has shown that regardless of whether a user intends to respond to their device, notifications alone are capable of increasing cognitive load and decreasing task performance [22].

Mark Weiser envisioned ubiquitous computing as disappearing into the background [30]; however, this is impossible if the user must remove and charge their wearable devices on a daily or even weekly basis. By taking power constraints and considerations out of the wearable itself, we allow it to slip into the background. Users can wear AlterWear on a daily basis, updating as frequently or infrequently as they like. If properly enclosed (See Figure 12), AlterWear could endure trips through the washing machine, inclement weather, and other wear and tear consistent with existing clothing and accessories. While our functionality is limited, this is intentional so that users do not have to worry about programming the devices, installing updates, syncing with additional devices, or removing to charge. We propose a restructuring of this human-device relationship by creating intentionally unobtrusive wearables that are low maintenance, do not need to be charged, and only provide updates on request.

ALTERWEAR SYSTEM ARCHITECTURE

Design Constraints

Engaging our motivations around limited power and novel lightweight interaction styles, the implementation of AlterWear was driven by several design constraints: (1) unpowered visual display, (2) lightweight quick interactions, (3) dynamic updates, and (4) adaptable across a wide range of wearable form factors. These constraints led to the physical design detailed below.

AlterWear Hardware Architecture

Our system contains a microcontroller, an NFC tag, an e-ink display, and a printed inductive coil. The coil provides the mechanism to wirelessly transmit power and data to and from the AlterWear platform (see Figure 4). We use commodity NFC hardware to establish wireless communication between close ($\leq$ 15mm) devices, to briefly power and exchange data with AlterWear. The e-ink provides a bistable display that has the desirable property of maintaining visual state even when it is unpowered. Updating e-ink displays is an extremely low power operation. At peak power, the entire system consumes

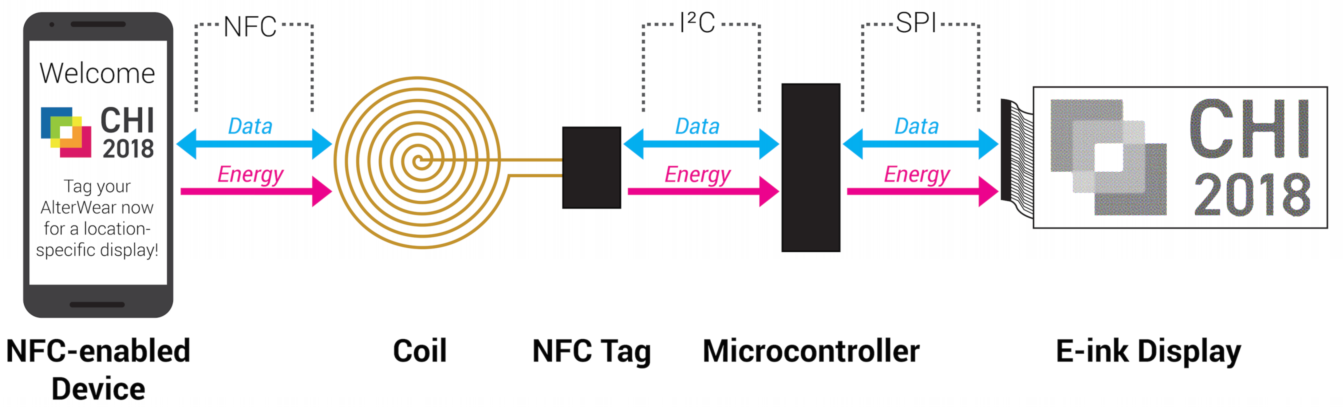

Figure 4. The AlterWear architecture includes an NFC tag, a microcontroller, and an e-ink display that are powered and updated through contact with an NFC-enabled device. When the device comes into contact with AlterWear, energy and data are transferred via NFC. The NFC tag then powers and transfers data via I2C to the connected microcontroller. Finally, the microcontroller powers and communicates with the e-ink display over SPI.

6mA at 2.7V (See Table 1). We are using NT3H1101 NFC Tags, Arduino Pro Mini microcontrollers, and e-ink displays from Pervasive Displays (Figure 3); however, these components could be swapped with equivalent components. Our larger prototypes utilize standard Arduino firmware and readily available libraries for updating e-ink displays and communicating via I2C.

Peak Power Requirements		
Current	Voltage	Time
6mA	2.7V	2.4 sec

Table 1. The e-ink display needs to maintain power during the update only. On an Atmel 328p chip, the time required to update the display is 2.4 seconds. The amount of energy that can be harvested varies based on a variety of factors. Voltage and current may change based on the strength of the RF field, the size of the tag antenna, and the distance between the NFC device and the coil.

When the system comes into contact with an object with embedded NFC, power and data is transferred from that object to the wearable display (A 4-byte write operation over NFC occurs in $<$ 4.8 ms to EEPROM and $>$ 0.8 ms to SRAM). This could be identification information, sensor data, a bitmap to be displayed, or a number of other data structures. Once this information has been transmitted, the e-ink display updates. This display is maintained even after the user has disengaged with the inductive field created by NFC. If the user sustains contact between the NFC-enabled device and their AlterWear display, the display will begin to animate. This interaction can easily be facilitated by designing AlterWear on pockets, phone cases, and other areas that are frequently in contact with the user's NFC-enabled phone.

While future iterations could leverage recent research in wireless charging [1] to update AlterWear at a distance, our current interaction involves touching the phone to the wearable display in order to power and update it (See Figure 2). Alternatively, displays could update in response to NFC from IoT devices and other sources.

Range of NFC

The range of NFC is greatly impacted by the size of the antenna, as well as the number of turns. Our custom hardware (Figure 8) has a coil size of 17mmx12mm with 6 turns, and has a range of 1mm. The Tag 2 Click NFC tag used in our larger prototypes (Figure 3) has a coil size of 20mmx20mm, 8 turns, and a range of 15mm.

AlterWear Design Considerations

Wearables demand attention to not only the functionality of the device but its ability to participate in an individual's personal fashion and visual aesthetic. As such, a significant consideration in our overall design is the ease and flexibility of personalization and customization of AlterWear devices.

Form Factor: Wearable form factors vary in their size, shape, and location on the body. Due to these differences, many applications are better suited for one garment or accessory over another. The user's personal style should also be taken into account.

Location of E-ink Display: As form factors vary in visibility, so do locations on form factors. The location of the e-ink display on a garment or accessory should be informed by existing cultural practices and affordances of the object. For example, the location of tee shirt displays should be informed by existing tee shirt designs. Jewelry form factors should similarly be informed by existing jewelry.

Type of E-ink Display: E-ink displays vary widely in size. The largest size supported by our implementation is 1.9”. Colored e-ink displays may be more widely available in the near future, although they will likely have different power requirements.

Location of Coil: The location of the coil may convey information about who should interact with it. Proximity to the e-ink display makes a more obvious interaction, while distance can provide a more subtle one. Additionally, coil placement influences the available modes of interaction.

Figure 5. Pocket tee prototype. Left: name tag application. Right: when the user places their NFC-enabled phone in their pocket, the phone continuously powers the display, and a simple animation is displayed.

Modes of Interaction

The design considerations previously outlined lend themselves to five distinct modes of interaction: direct tagging, disjointed tagging, animated displays, obscure updates, and situated updates.

Direct Tagging: For direct tagging, the e-ink display and inductive coil are co-located; the user tags the display directly in order to update it (see Figure 2). This mode of interaction is intuitive and therefore well suited to social interactions.

Disjointed Tagging: For disjointed tagging, the e-ink display and inductive coil are isolated in separate locations; the user tags one location of the body to update a display on another (see Figure 9). This mode of interaction is discreet and well suited for more personal displays; onlookers do not immediately know where and how to interact with the display. Disjointed tagging is also useful for displays in hard-to-reach locations. For instance, instead of straining to reach a display on the back of a jacket, the coil could be located in a more accessible location, such as the front or the sleeve. Finally, disjointed tagging allows for more subtle interactions. Rather than conspicuously tagging a display and consequently calling attention to it, an isolated coil provides for more discreet interactions

Animated Displays: If the coil is near a reliable power source, the display can cycle through a series of images to create an animation. Depending on the choice of images, the animation may be subtle, or eye-catching. Designers of AlterWear can enable animated displays by situating the inductive coil in locations that are frequently in contact with NFC (see Figure 5). These locations include places that the user normally keeps their NFC-enabled Smartphone, such as the inside of a pocket or a bag. The display will animate as long as the coil remains in contact with the NFC-enabled device.

Obscured Updates: NFC is able to transmit both power and data through fabric and other thin materials (less than 15mm). Designers and users can leverage this property to enable obscured updates. Without taking out their NFC-enabled Smartphone, users can simply tag their AlterWear to the phone through a bag, backpack, or pocket. This mode of interaction is best suited to form factors that are more maneuverable, such as bracelets, watches, shoes (Figure 7), and false fingernails (Figure 8).

Situated Updates: While the previous modes of interaction utilize NFC-enabled Smartphones, IoT devices and public infrastructure can similarly update AlterWear devices (see Figure 9). Similar to obscured updates, this mode of interaction is best suited to form factors that are more maneuverable, or form factors that are often removed, such as gloves, jackets, bags, and hats (Figure 6).

Figure 6. Baseball hat prototypes. Left: Hat prototype with AlterWear display on the front panel. Right: Hat prototype with AlterWear display on the side panel. Below: Close up of the side design. We added a simple animation when updating the display to give the appearance of sparkling or twinkling stars.

EXEMPLAR PROTOTYPES

To demonstrate our architecture and resulting battery-free wearable displays, we designed six initial prototypes.

Pocket Tee

Our shirt prototype (see Figure 5) is a modified pocket tee. We augmented the existing pocket with a 2.0” e-ink display and embedded the NFC coil directly below. The location of this coil supports two modes of interaction; it’s proximity to the e-ink display enables direct tagging, whereas its location in a pocket affords animated displays. If a phone is carried in the pocket, the display can be continuously powered and animated. The microcontroller and other components are discreetly sewn into the pocket. We chose this form factor because tee shirts are culturally accepted as a form of expression, and it is fairly common to see logos, designs, text, and other visual cues across the chest. Furthermore, the pocket provides a natural substrate for small embedded displays.

Imagine Walter Ware is heading to a job fair. He realizes it would be nice to have a name tag for the event, and quickly updates his shirt with his name, title, and a little drawing he did of his personal logo. After he arrives at the event, he decides the drawing feels unprofessional, so he quickly updates the display to remove it. He notices his favorite company is there, and knows they’re looking for a UX designer in particular, so he updates his job title to UX designer before approaching their table.

Baseball Hat

We designed and prototyped two hat prototypes (see Figure 6). These prototypes are standard baseball hats that have been augmented with AlterWear. We chose this form factor because hats are frequently used to express interests and contextual cues, such as sporting teams and events. Hats are also easily removed and therefore ideal candidates for situated updates (see Figure 9). Each of our hat prototypes has an e-ink display embedded in the crown of the hat (in either the front panel, or a side panel), and an NFC coil hidden in the back. The separation of coil and display supports disjointed tagging. This

Figure 7. Sneaker prototype. Left: Discreet display on the inside heel of the left shoe. Right: Public display on the toe of the right shoe. AlterWear devices are highly contextual. A single artifact can be both personal and public depending on the location of the display.

discreet form of input is desirable over direct tagging, as the user cannot see the display that they are wearing, and likely do not want others to know how to update it. Additionally, the back of the hat is more likely to come in contact with external surfaces and objects when not being worn, further enabling situated updates. The microcontroller and other components are discreetly sewn into the hat.

We created two baseball hat prototypes. For the first prototype, we added an e-ink display to the front panel of the hat. This is ideal for showcasing logos or designs. We chose a 1.9” e-ink display: the display is large enough to be visible, yet not so large that it compromises the appearance or feel of the hat itself.

For the second hat prototype, we laser-cut 3 star-shaped openings into the side panel of the hat, and attached a 1.44” e-ink display behind them. The e-ink is programmed to make the pattern stand out or fade into the background, as desired. This display is more subtle and demonstrates how AlterWear can be more abstract.

Walter and his family love to attend sporting events, but they each prefer a different sport. Last week, Walter and his daughter enjoyed a hockey game. Today Walter is going to a football game with his son. As they walk into the stadium, Walter presses the back of his favorite baseball hat to the particular section of the turnstile, and the display updates from the logo of the hockey team to show the logo for the home team. This weekend, Walter will update the display to show a custom design he made in support of his daughter’s softball team. He is relieved he doesn’t need to own more than one baseball hat, but can still easily update the display so it’s appropriate to the changing context.

Sneaker

We also augmented a pair of sneakers (see Figure 7). We replaced the logo with an 1.9” e-ink display and added a 1.44” e-ink display to the vamp. Both locations are rigid and therefore ideal for introducing electronics. In both shoes, the coil is adjacent to the visual display. While the close proximity of display and coil allows for direct tagging, the shoe form factor enables obscured updates. Rather than taking their Smartphone out of their backpack or bag, the user can discreetly check for updates by moving their shoe next to their concealed phone. These updates are then glance-able in their respective locations.

Sneaker Logo: The distinctive logo of this brand of sneakers provides an obvious location for personalized display. The slightly hidden location on the inside of the ankle is a good fit for functional or private designs. As the logo is already a busy part of the shoe, added designs at this location are discreet.

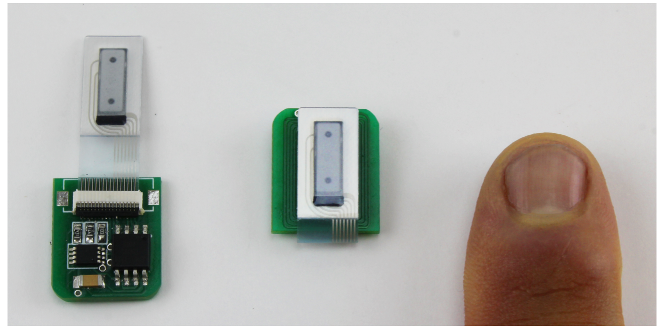

Figure 8. The fingernail AlterWear design with custom circuity and e-ink (Left) and folded over into a more compact fingernail form factor exposing the dynamically programmable e-ink dot pattern (Middle) next to an actual fingernail (Right).

Sneaker Vamp: On the other hand[1] the vamp is a popular location for sneaker adornment, such as Sharpie inscriptions and other doodles. The existing cultural practices around drawing on the vamp, and the rigidity provide a culturally relevant and structurally sound site for augmentation. The display here references this existing practice of decoration for a more social, purposefully performative display.

Walter is meeting his daughter Sal for lunch. He arrives early, so he sits down, crosses his ankle over his knee, and tags his logo display to check his current step count (See Figure 11). He’s grateful for the information, but happy that he doesn’t need to open an app to see it, and glad that the display will subtly blend with the design of the shoe. When Sal arrives, she tags the vamp of her own sneaker and an 8-bit heart she’s designed appears (See Figure 7). The next morning, Walter sees the 8-bit heart again and it reminds him of the lovely conversation they shared the day before.

False Fingernail

Our final prototype is a false fingernail form factor (see Figure 8) based on previous work [4]. This prototype uses a small, 5-dot segmented e-ink display along with a custom designed hardware board with embedded inductive NFC coil. The entire PCB measures 18.2mm long, 15.3mm wide and 3.55mm thick. We fabricated this wearable to demonstrate that AlterWear hardware can be can be implemented at a very small scale and can be applied to cosmetic form factors. Directly underneath the e-ink display, the location of the inductive coil supports direct tagging. Additionally, the fingernail form factor enables both obscured and situated updates. A user can check for updates by simply placing their hand over their concealed phone; the fingernail could be powered and updated through everyday interactions with Smart objects.

Walter is anxious to know if his important package has been delivered; however, it is only his third day as a UX designer and he doesn’t want to be seen on his personal phone at work. While glancing over some new designs, Walter rests his hand on his thigh, subtly tagging his nail to the phone in his pocket.

[1] foot

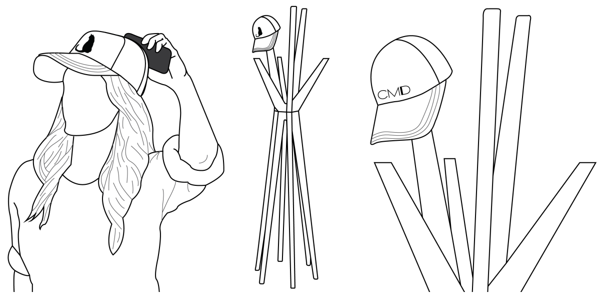

Figure 9. Disjointed tagging (left) and situated updates (right). Camila is volunteering at her local animal shelter. She tags her phone to the back of her hat to update the display on the front. It now showcases the shelter's logo. When she returns home, she hangs her hat on an NFC-enabled hat rack, which updates the hat to her default design: her initials.

When he picks up his pen to annotate the designs, he briefly glances at the display to see that a new dot has emerged: his package is safe at home. Walter feels relieved and re-energized as he continues his work.

APPLICATIONS

As with many wearables, the form factor, location on body, and type of display are all important considerations when determining the class of applications. We present here a selection of proposed use cases for AlterWear.

Notifications: In contrast with the notifications of many existing wearables, which vibrate, flash, or otherwise do their best to command attention, AlterWear updates only when desired. This makes AlterWear ideal for pull notifications. Rather than unlocking their phone and opening an app, users can simply tag the phone to their AlterWear to view relevant information and updates. Examples include viewing health or fitness data, checking non-urgent logs from a sensor, and confirming if the details of an event have updated. We emphasize that AlterWear provides notifications at the moment the user needs them, rather than the moment they become available.

Notifications can also be discreet. Users can utilize obscure updates to check for notifications: simply tag AlterWear to their phone through a backpack, pocket, or other thin material, and view the updated information at an appropriate time. Personal information can be displayed in discreet locations (see Figure 11).

Personal Expression: AlterWear can be used for personal expression and as a public-facing display. AlterWear displays are public displays in the same sense that wearing a logo, a graphic t-shirt, or a hat is a public display; however, our prototypes render these displays dynamically, allowing the user to update them quickly, discreetly, and at any time. A small display embedded into an article of clothing or an accessory renders the entire piece dynamic, and can provide a small but playful site for creativity.

Social Engagement: AlterWear fosters social connection. The act of tagging a display on another person and sharing your design with them can promote intimacy and connection. The data shared can be intimate, such as how NFC is currently used to share photos, videos, and contact information, but the *nature* of the interaction is also intimate. The act of tagging a friend to update their display may further enhance the sense of

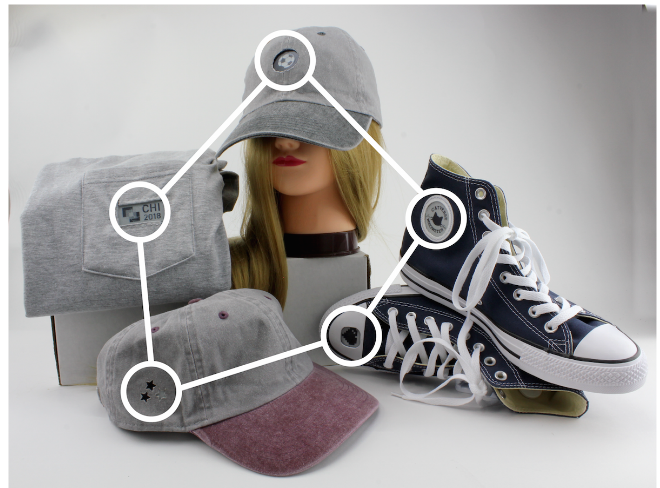

Figure 10. Our designed AlterWear prototypes. These prototypes vary in size, form factor, and location on the body. Several of these prototypes are more suited to public applications and displays, whereas others are more subtle and personal.

closeness, as it brings an element of mediated social touch into the interaction [6]. We expect that due to the intimate nature of touch, users would only want to share/exchange displays with close friends, but that this would enhance their sense of social connection. A user can share a design by updating their friend's AlterWear directly through tagging, or by sending them the designs to tag themselves.

Location-Based Interactions: Rather than being selected explicitly by the user, designs could be tied to particular locations or events. For example, everyone at a corporate party, a basketball game, or other large event could access a design unique to that event. Users could display the design while at the event, and it can also act as a digital memento that they can keep and display.

USER STUDY

We conducted a user study to probe perceptions of wearable battery-free displays, and to evaluate our designed prototypes.

Participants

We had thirteen participants provide feedback on our AlterWear prototypes (7 female, Average age 23.6). Participants self-rated their experience with wearables. 11 stated that they own "one or more" wearable devices and rated themselves as "using it frequently". The other participants used a wearable device "often" or "occasionally", or used to own one.

Participants were recruited from University and local mailing lists and were invited to meet with us in our studio location for an hour-long workshop. They were compensated at the rate of $20/hour. We first gathered background experience with wearables, then invited them to interact with our designed prototypes. We next conducted an informal interview, and finally ended with a brainstorming activity and assessment questionnaires. All interview meetings were audio recorded, transcribed, and analyzed, following best practices for a qualitative interview [31].

Qualitative Findings

Social and Individual Uses Both Desired

All users appreciated the potential for social games or interactions enabled by the devices. In particular, participants were drawn to the idea of location-specific geofilter type interactions. Three users specifically expressed interest in creating a cohesive social experience at a party or other event. Participants universally felt that a personalized display would lower barriers to social interactions and foster connection.

> **P7** The display could give you some details, some kind of funny information about the person and then you could start from there...It could make the conversation less superficial, and less official, and more intimate and more social.

While users expressed interest in the displays helping to ease social interaction, six users (five male) expressed a rapid and comedic sense of extreme horror at the idea of their friends having the ability to update their display. These users immediately felt that the display would be used to share inappropriate material, and laughingly insisted that they wouldn't trust their friends. **P10** "Oh no no no no way, no, I would not let my friends have access." **P1** "Hahaha definitely not, that would be way too risky." **P13** "I would not be interested in that at all."

Generally, participants wanted control over what designs appeared on their clothing. No user expressed interest in autonomously generated patterns or displays, or automatically updating displays with a design they didn't choose. About half of the participants were drawn to discreet, personal, and functional displays, whereas the others were more intrigued by outward-facing, public displays for fashion.

Customizable Fashion is Appealing as "Extension of Self"

Universally, users recognized that their fashion choices were highly contextual, and responded very positively to the idea of a display that could be easily updated. **P2** If it's a thing that can be changed, then I definitely want it to be changed. However, users weren't sure that the changes in the prototype displays were always significant enough to register as a 'different style'.

Ten users preferred the animated displays to the static ones. They commented that a moving display on your person would be unique and eye-catching, unlike anything they had seen before. As our prototypes are all wearable and closely approximate familiar form factors, such as clothing and accessories, participants tended to view them as "extension of self": intimately intertwined with their sense of personal identity, and influencing the way in which others perceive them.

One user was an artist, and expressed interest in using the display to test out her graphic designs. She imagined updating a design throughout the day, and seeing what kinds of reactions she might get.

Novel Functionalities Justify Additional Wearables

The notion that wearables are meant to be functional, and to track, notify, or otherwise inform was strong with 10 of our users. Three users thought that tracking or sensor data of some kind was part of the definition of a wearable device. A device that was designed to help express *style* was a novel idea to these users. About half of these participants were not interested in using AlterWear for fashion and were instead more intrigued by functional applications and instances.

While we had initially desired to design a communication protocol between AlterWear devices, most of our users were very opposed to this idea, and envisioned having just one AlterWear device. The exception was multiple devices with unique functions, in which case the need for more than one device was more clear.

Preferred On-Body Location Highly Variable

Participants varied widely in where they felt would be an appropriate location for AlterWear. Customization is clearly especially important in wearable devices, where the form factor and location is influenced not only by function, but by the user's sense of aesthetics and notions of presentation of self. One user thought the sleeve would be ideal, and another thought a sleeve-based display would be strange. Another user was adamantly opposed to any kind of display on pants, and described a display on a skirt or a dress as "awfully weird". It's impossible to anticipate all of the fashion choices people would desire, but a flexible, customizable design can support a range of aesthetic choices.

Pull Notifications Viewed as Less Intrusive

Ten of our thirteen participants vehemently complained about receiving notifications on their wearables or other devices. Many commented that they immediately turn off all notifications going to their wearable devices, and see no added benefit to getting the notification on the wearable interface. **P8**: It doesn't need to be so accessible that it's forcing itself on you. In particular, they resented the intrusiveness of beeps, buzzes, or alarms:

> **P8** With the current way wearables are working, they're adding more distractions to your life rather than getting rid of distractions.

Five users with high levels of experience using wearables conceptualized devices as needing care and support from their owners:

> **P1** I'd worry about having a lot of devices that all want something from you.

Users frequently personified existing wearables, describing them as **P7** too many dead items trying to simulate life, or in agentic terms.

> **P7** It's not like dystopic - too scary. It's more like too annoying. Oh, now the hat wants to tell me something, or now the box wants to.

In contrast, a less interactive system was more appealing.

> **P6** Anything that requires less input from me, that means lesser engagement with the gadget from my side, I'd always prefer that.

Battery-less Interfaces Perceived as Less Demanding

Five users specifically identified the frustration involved in maintaining batteries as a reason for not wanting to use a new wearable device. **P12** It's annoying that you have to charge another extra device. **P9** I wish you didn't have to recharge them as often.

These users commented positively on the battery-less nature of AlterWear:

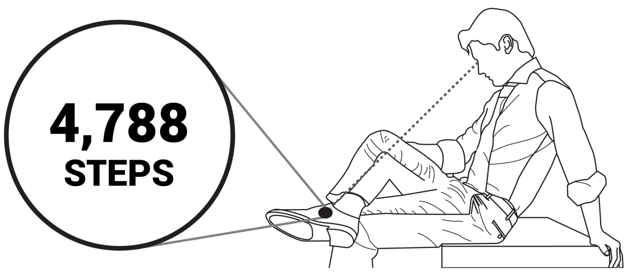

Figure 11. Example application of a discreet display. The user checks fitness information displayed discreetly on the inside of his heel.

> **P5** I do like that you can just use you phone to power it so you don't have to charge it or anything, and carry a charger around with it.

We suspect that a few of the other users didn't fully absorb the fact that AlterWear requires no battery, even though it was stated several times. For future work, we plan to have a more extensive user study where participants actually take home the AlterWear devices for an extended period of time, and fully experience their longevity in the absence of charging.

Integrated Form Factor Supports Adoption

Participants positively responded to the more seamlessly integrated form factors, such as the shoe. One user particularly responded to this form factor.

> **P4** It's not something I would have to wear on top of something else, like you have to wear your shoes.

The more seamlessly the e-ink displays were integrated into the prototypes, the stronger and more positively participants reacted. A number of users were attracted to the simple and neutral paper-like appearance of the e-ink display, which they preferred over other types of displays that emit light.

> **P1** From afar, it kinda looks neutral. It looks like a regular shirt.

A minority of users viewed the e-ink displays as distinct and separate from the garments. These users did not like the screen-like aesthetic. **P4** I don't like the square. **P1** Most of these seem to be hidden behind a window.

Physicality of Interaction Affords Intimacy

Participants were intrigued by the social interactions afforded by our prototypes. They wanted to share designs with their friends, and specifically identified the physical "tag" gesture as supporting a sense of intimacy and closeness. Four participants saw the touch interaction as specifically important to the intimate experience.

> **P1** it would be a good way to connect with people. If you could touch the [phone and their clothing] together and have a bond.

Half of the participants felt that the required physical interaction naturally resolved issues of privacy and consent: if you're close enough friends to physically touch, then you're close enough to update each other's designs.

> **P3** If you have to touch them to transfer the design, that [is] totally different. You do it in front of their face so you have their permission to do it.

Participants also thought the act of tagging helped maintain their control over what appeared on their clothing.

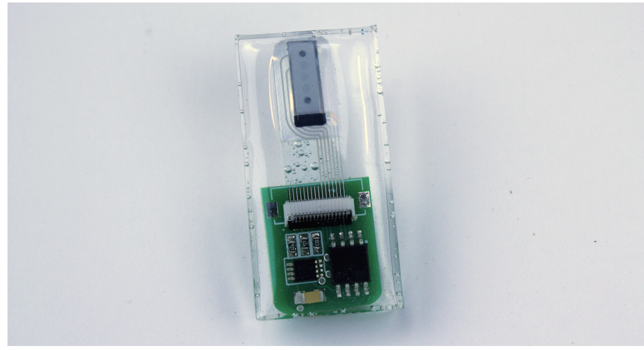

Figure 12. To demonstrate durability and longevity of AlterWear devices, we completely enclosed our fingernail prototype in resin. The prototype is durable, waterproof, and still entirely functional.

> **P5** I would want the option to show up, and I could change it to that, but not automatically changing it without me actually [tagging] it.

One user thought the tagging gesture was too much of a barrier to using the displays, but the majority of users thought the interaction was either good, or a worthwhile tradeoff in exchange for not having to maintain a battery. One user actually preferred the tagging gesture and perceived the functionality of the device more clearly because of it. **P5** I would want to keep the [tagging], rather than just clicking [a button]...so I don't have to check that it updated, because I know it did.

Synthesis

Here we briefly synthesize our findings. In terms of form factor, we found that participants highly rated well-integrated form factors, viewed on-body wearables as an extension of their own identity, and expressed interest in a variety of personal and social functions. For the interaction style, participants positively responded to the idea of a battery-less device, a physical gesture to update display, and only pull notifications. We encourage designers of wearable interfaces to consider how much effort is involved in maintaining on-body devices, and mentally managing notifications.

DISCUSSION AND FUTURE WORK

Two-way communication: Currently, AlterWear uses NFC to read information from the NFC-enabled device; however, the communication protocol works in both directions. Future iterations of AlterWear could utilize this back-channel to communicate and send data back to the NFC-enabled device. This would enable interactions where an NFC-enabled phone could 'read' an AlterWear device, and copy the design to additional AlterWear devices. Sensors could also be embedded into AlterWear to provide data to inquiring NFC-enabled devices. However, these embedded sensors must be small and low-power. Reasonable sensors include accelerometers, photo-diodes, temperature sensors, and the like.

E-ink displays: The e-ink displays in our prototypes are all rigid, rectilinear, and monochrome (see Figure 10); however, e-ink displays are becoming increasingly available in commercial markets. These e-ink displays are available in custom non-linear shapes, flexible form factors, and a limited range of colors. Further customization can be achieved by personally fabricating custom displays [24] and exploring other materials, such as electroluminescence.

Power considerations: As mentioned previously, future iterations of AlterWear could leverage corporate research into wireless power [1]. Additionally, AlterWear could be augmented with capacitors to store charge for on-demand interactions.

Durability: Since the electronics of AlterWear never need to be accessible for charging or programming, AlterWear can be completely encapsulated in waterproof enclosures. To demonstrate this, we completely enclosed our fingernail prototype, as well as an NFC Tag 2 Click breakout board, in clear resin (see Figure 12). We fully immersed both devices in water, and left the Tag 2 Click submerged for a period of three days. Both devices remain intact and fully functional. Thus, AlterWear can be rendered robust and sturdy, and could endure many trips through the washing machine, adventures through inclement weather, changes in trends, hand-me-downs through siblings and friends, eventual abandonment at a donation site or thrift shop, and new life through repurchase. These artifacts could take on a life of their own through multiple owners, and through various interactions and uses.

Advantages over existing wearables: In addition to their aforementioned durability and longevity, AlterWear provides several other advantages over existing wearable devices. Rather than the 'one size fits all' mentality prevalent in current wearable technologies, AlterWear provides an array of diverse form factors and interactions that are driven by context. AlterWear also responds to the 'one device to rule them all' way of thinking by intentionally limiting interaction. This limited functionality is paralleled by limited responsibility for the user to charge, care for, and even think about their devices. AlterWear's restructuring of notifications to be user-driven, rather than device-driven, has an advantage in that users don't have to dedicate cognitive load to thinking about their devices and anticipating notifications [22]. Finally, AlterWear enables intentionally performative and playful interactions that were previously infeasible with existing wearable technologies.

CONCLUSION

In this paper, we presented AlterWear: an architecture for battery-free wearable displays supporting opportunistic interactions. We hope that AlterWear will inspire and enable new wearable devices that expand the ecosystem of functional and fashionable wearable technologies.

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