Probing User Perceptions of On-Skin Notification Displays

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On-skin displays are emerging as a wearable form factor for the display of information; however, the perception of using such devices in public could determine whether they are eventually adopted or rejected. This study investigated the means by which on-skin notification displays are perceived by the general public. We adopted a mixed-methods approach to the analysis of results from an online survey (n = 254) and in-lab interviews (n = 36) pertaining to the novel form factor, device materiality, and envisioned use cases. The study was conducted in the US and Taiwan in order to examine cross-cultural attitudes toward device usage. The results of this structured examination provide valuable insights into the design of on-skin notification displays for everyday use across cultures.

CCS Concepts: • **Social and professional topics** → **Cultural characteristics**; • **Human-centered computing** → *Empirical studies in HCI*;

Keywords: On-skin interfaces; user perceptions; wearable displays; color-changing notifications

244

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1 INTRODUCTION

Visual notifications [13, 66] are cues used to inform an individual of status updates or the availability of new information on mobile devices. As sensor devices become increasingly miniaturized, wearable and on-skin devices are expected to become increasingly prevalent in applications from healthcare [5] to beauty technology [69], and virtual and augmented reality [6]. On-skin devices are worn directly on the skin surface for an extended period, such that visual notifications can be seen by the users as well as others when used in public. Designing socially acceptable on-skin devices for daily use requires an understanding of the means by which observers perceive the appearance of visual notifications on their skin and on the skin of others.

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1.1 User Perception Matters When Designing On-Skin Notification Devices

Researchers have addressed various aspects of wearable technology (e.g., device size, information complexity, body location, and display color) and their effects on cognitive responses to visual notifications (e.g., reaction time or workload) [13, 16, 30, 46, 47, 66]. It is also important to understand the perception of visual notifications in social contexts and how this may influence the acceptance of the technology. Users are expected to wear these devices for an extended duration (including a range of social situations); therefore, the way that others perceive the devices is also very important [45]. To the best of our knowledge, this is the first study to examine the user perception of receiving visual notifications via on-skin devices in everyday scenarios.

1.2 Exploring the Impact of Culture on the Design of On-Skin Notification Devices

Researchers have clearly demonstrated the importance of understanding cultural proclivities in designing wearable interfaces deemed socially acceptable. Studies have looked into the effects of body location [57], gestural interaction [57], and social settings [15] on the adoption and perception of mobile and wearable technologies. With the advent of devices worn directly on the skin, it will be necessary to elucidate the complex social and cultural relationships associated with intimate body-borne technologies of this type [76]. To the best of our knowledge, no previous studies have investigated cross-cultural perceptions toward the application of notification displays directly on the skin.

Theorists have identified a variety of cultural factors that influence the perception of visual parameters, such as the colors used for visual notifications [48, 78]. Kayan et al. [39] focused on the influence of individualism-collectivism on instant messaging beyond the Western perspective. They built on the observation that westerners tend to emphasize individual needs over the needs of the entire group, whereas people in Eastern countries tend to emphasize self-sacrifice, reliability, and benefit to others [63]. In this study, we sought to derive a general overview of perceptions pertaining to this technology by performing analysis in a western culture (the US) as well as an eastern culture (Taiwan). We aim to make an empirical contribution to design practices by addressing the following research questions:

- What are the user perceptions pertaining to the design of devices for on-skin notification?
- What are the cultural differences pertaining to these perceptions among users in the US and Taiwan?

The remainder of this paper is organized as follows. Section 2 presents a review of the literature related to on-skin interfaces and displays, mobile and wearable visual notifications, user perceptions of wearable technology, and cross-cultural studies on the effect of cultural norms on wearable technologies. Section 3 outlines the methods used to characterize perceptions of visual notifications in the US and Taiwan, including an online survey (1st stage) and in-lab interviews (2nd stage). Section 4 describes results in the two stages of data collection. Section 5 presents a discussion of the research findings. Section 6 outlines the limitations of this study. Section 7 presents conclusions and outlines our future work.

2 BACKGROUND & RELATED WORK

This section summarizes existing research on on-skin interfaces and displays, mobile and wearable visual notifications, user perceptions of wearable technologies, and cross-cultural investigations on the usage of wearable technology.

2.1 On-skin Interfaces and Displays

On-skin interfaces render the user's body as an always-available surface for sensing touch input [37, 44, 51, 73, 74], displaying visual output [34, 37, 70, 72, 74], providing haptic feedback [29, 75], sensing gestural interactions [36, 49], and monitoring physiological signals [41]. Device fabrication of on-skin displays generally involves the lamination of environmentally reactive pigments (e.g., heat-reactive [35, 37, 72] or UV-reactive pigments [5, 12, 34]) into a skin conformable form factor. Many on-skin displays present a gradual gradation of color to avoid the harsh appearance of binary digital displays [20]. Another approach is to incorporate LEDs on the skin surface; however, those devices are not as thin or unobtrusive as some designs [44, 68] and require advanced manufacturing capabilities [3]. Recent prototypes of electro-luminescent displays [52, 74] provide response times faster than those of thermochromic pigments; however, they require relatively high voltage (148V) drivers. Most of the research in this field is currently focused on the technical aspects of on-skin displays. To the best of our knowledge, there has been no previous research into the user perceptions of these devices. This study focused on a thermochromic-based display, due to its slim design, ease of fabrication, and ease of integration for on-skin wear.

2.2 Mobile and Wearable Visual Notifications

Since cultures vary in their perceptions of design factors, we continue to explore how design factors in previous research impact people's perceptions toward visual notification. Mobile and wearable devices employ a range of modalities to inform users about incoming notifications [60], including visual, auditory, tactile, haptic, and thermal feedback. Notifications are used to remind users of situations involving their mobile system (e.g., low battery warnings) or applications (e.g., reminders from health apps [53]). Visual notifications on mobile phones vary the color of the text and/or the background color [7]. Several studies [13, 16, 30, 46, 47, 66] have investigated the design and usage of visual notifications (e.g., information complexity, display colors) and their effects on cognitive responses (e.g., reaction time or workload). Tarasewich et al. [66] conducted an experiment to determine how the low-resolution displays used in mobile devices affect cognitive performance in terms of reaction time and accuracy. Campbell et al. [13] performed an experiment to measure the degree to which information complexity in visual notifications influences the time required for message comprehension. Lyons et al. [47] investigated the degree to which the size, frequency, and color of visual prompts on smartwatches affect users' reaction times. Harrison et al. [30] studied the time it took participants to notice visual stimuli on a small sensor-display mounted at seven locations on the body.

Researchers [16, 46] have designed a variety of peripheral notification technologies to avoid disrupting primary real-world tasks. Costanza et al. [16] designed a wearable peripheral display embedded in eyeglasses (called Eye-q) to deliver unobtrusive visual cues. Lucero et al. [46] prototyped an application (called NotifEye) that allows users to receive social network notifications on interactive glasses without compromising one's attention to their surroundings. Recent advances in sensor miniaturization have made it possible to present visual notifications directly onto the user's skin [5, 6, 69]. However, the advent of unconventional form factors has raised concerns as to their acceptance in public use, which we aim to distill through our studies.

2.3 User Perceptions of Wearable Technologies

Social acceptability stems from sociologist Goffman's [25] concept of "impression management," in which the "performers" present themselves in front of "spectators" in seeking to assimilate into society. Despite the efforts of many researchers in the study of social acceptability [42], the underlying factors are still not well understood. The Wearable Acceptability Range (WEAR) scale [40] is an attempt to quantify factors related to the acceptance of wearable devices. One comprehensive survey paper by Koelle et al. [42] highlighted the need for nuanced mix-methods to capture the complexity of social acceptance. In this study, we adopted that approach in our combination of surveys and in-lab interviews.

A variety of wearable form factors have been investigated from the perspective of social acceptance [24, 77], including mobile devices and gestural interactions [50, 50, 58, 59] to head-mounted displays (e.g., Virtual Reality (VR) headsets) [11, 19, 55, 62] and smart glasses [43, 56]. Efforts to create wearable forms for placement closer to the body has increased interest in e-textiles and on-skin interfaces. Holleis et al. [31] investigated the ideal placement of capacitive touch sensors on textiles. Profita et al. [57] used an online survey in the US and Korea to investigate user perceptions of embroidered textile touch sensors. The e-textiles project referred to as Pinstripe [38] reported some areas are deemed out-of-bounds for device placement due to social constraints. Analysis of interactions with a smart suit prompted Toney et al. to define a measure they called "social weight" [67] as the degree to which device interactions compromise social interactions. In this work, we focus on the under-explored field of on-skin output displays.

2.4 Impact of Cultural Norms on Usage of Wearable Tech

Anything worn on the body is subject to criticism by others, and cultural norms play an important role in shaping one's visual perception [48, 78]. What is deemed "acceptable" also varies across cultures and scenarios, as each social group tends to follow different value systems [17, 22]. These cross-cultural differences also occur when people use wearable technology in daily life. Since people wear on-skin devices for extended periods, it is expected that they would receive visual notifications while in public. Researchers [15, 57, 76] have recognized several culture-related design factors that could affect user perception towards wearable technology. Campbell [15] studied variations in mobile phone use across four countries. Japanese and Taiwanese participants reported greater tolerance for mobile phone use in a theater, classroom, and restaurant than did those from the US and Sweden. Profita et al. [57] investigated South Korean versus US perspectives towards an e-textile touch sensor. Korean participants reported fewer gender differences in terms of preferred gesture locations. You et al. [76] studied Taiwanese (TW) versus US perspectives towards an on-skin touch sensor, with TW participants expressing more reservations toward the use of devices in public. Previous CSCW research has examined cross-cultural differences in the use of instant messaging [39], social media [18], and online mental health support forums [54]. However, to the best of our knowledge, no study has examined the preferences or perceptions related to visual notifications using on-skin devices. We build on these studies to extend cultural investigations to on-skin notification devices.

3 METHODS

Our objectives in this study were to identify perceptions of on-skin notification displays (via surveys) and also to elucidate the reasons underlying those perceptions (via interviews). The online surveys conducted in the US and Taiwan enabled the collection of data from 254 individuals covering a broad demographic in two distinct cultures. Semi-structured interviews with 36 participants (again conducted in both countries) provided further insight into their perspectives. The interviews centered around a novel on-skin notification device developed in this study (referred to as SkinDisplay). Specifically, we used SkinDisplay as a material probe [33] to draw out insight on perception towards the emergent materialities of the device, and also cultural reasons that may impact perspectives.

Fig. 1. Participant skin tone color depth selection cards.

3.1 Participants and Recruitment

We recruited our online or interviewing participants for the two studies (i.e., online survey and interview studies) through Facebook personal wall posts or groups, online discussion groups, emails, or snowball sampling.

3.1.1 Online Survey. The first stage of the study involved the recruitment of 254 participants, including 127 participants in the US (68 males and 59 females), and 127 participants in Taiwan (68 males and 59 females) aged 18-70. The average age was 32.17 (SD=9.54) in the US and 33.50 (SD=10.85) in Taiwan. There was no significant difference between the two groups in terms of age distribution (p=0.24 using independent samples t-test) or gender distribution (identical). The ethnic makeup of the US participants was as follows: Caucasian (58%), Asian American (33%), African American (3%), Latino (3%), mixed race (2%), and other (2%). All participants in Taiwan were East Asian. All participants passed the Ishihara's color blindness test [32]. Upon survey completion, the participants received a small gratuity of USD 15 per participant in the US and NTD 250 for each participant in Taiwan.

3.1.2 Semi-Structured Interview. We spent three months to recruit a total of 36 participants for the semi-structured interviews, which included 18 participants in the US (8 males and 10 females), and 18 participants in Taiwan (9 males and 9 females), aged 21 to 44. The average age was 29.6 (SD=5.97) in the US and 30.0 (SD=7.15) in Taiwan. There was no significant difference between the two groups in terms of age distribution (p=0.84 using independent samples t-test) or gender distribution (p=0.64 using Chi-squared test). The skin tones among US participants were as follows: fair (28%), light (33%), medium (28%), dark (6%), deep (6%). The skin tones among Taiwanese participants were as follows: light (28%), medium (50%), medium-dark (22%). We employed the skin tone color depth cards presented in [8] (Fig. 1), from which participants self-selected a skin tone by matching their hand to the closest color. All participants passed both the Ishihara's color blindness test [32] and the Farnsworth D-15 test [2] during the pre-study phase for testing color vision deficiency. Upon survey completion, the participants received a small gratuity of USD 25 per participant in the US and NTD 250 for each participant in Taiwan.

3.2 SkinDisplay: On-skin Notification Prototype

This section introduces *SkinDisplay*, the on-skin display prototype developed for this study. The on-skin display comprised two components: (1) a color-changing on-skin overlay connected to (2) a custom-designed circuit board for computation and wireless communication. Figure 2a presents an exploded-view diagram of the complete device.

3.2.1 On-Skin Overlay. The on-skin overlay consisted of 4 layers stacked one on top of the other (Figure 2a). The top layer is a color-changing silicone overlay (Figure 2b) containing thermochromic pigments with a 40°C transition temperature (Shenzhen Dahua Brother Industrial Company). Essentially, the thermochromic pigments change color when activated by underlying resistive heating traces (AGSIS silver-plated nylon thread). Note that the base color (white) transitions to a final color in 30 seconds at room temperature and takes 1 minute to cool down. A thin copper sheet (Dilwe copper foil sheet) lies beneath the resistive heating traces to spread the heat evenly

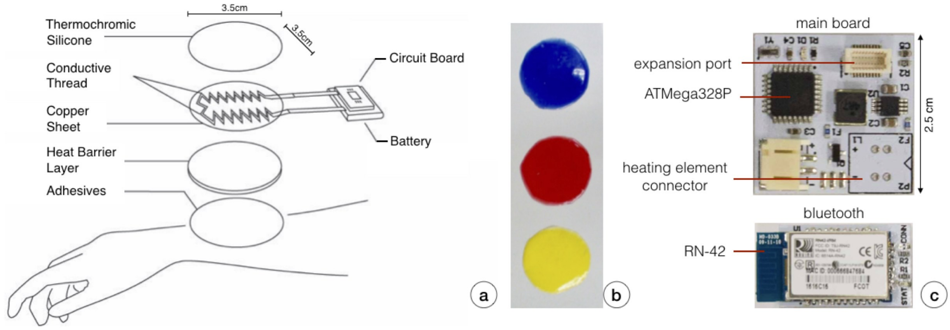

Fig. 2. (a) Exploded-view diagram of color-change resulting from the application of on-skin display; (b) color-changing thermochromic silicone skin overlays in the three colors adopted for this study; (c) custom PCBs connected to the skin overlay.

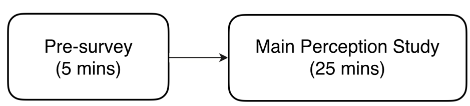

Fig. 3. Online survey protocol.

throughout the silicone overlay. A heat barrier (MoO1deer heat barrier tape) insulates the device from the skin to protect the wearer in the event of device overheating. All of the layers are attached to the body via nail art sticker adhesive.

3.2.2 Color for On-Skin Display. It would be not feasible for the prototype to encompass every color in the spectrum; therefore, we opted for the RYB (red–yellow–blue) primary color triad [65] as a starting point for our analysis of user reactions. RYB comprises the primary colors of a standard makeup artist's pallet, which can be used to create all of the other colors in the spectrum. We adapted the primary colors using in cosmetics and body art for the on-skin displays.

3.2.3 Custom Designed Circuit Board. The on-skin overlay was connected to a custom designed circuit board (Figure 2c) powered by a 5V Lipo battery. The electrical system had three requirements which could not be satisfied by any off-the-shelf micro-controller: on-skin electrical safety, miniaturization, and very specific power requirements. Concerns of on-skin electrical safety prompted us to limit the operating voltage to 5VDC, shield the skin from heating elements, and lay out the circuitry to prevent electric shock. The need for miniaturization led us to create a modular design using peripheral attachments (i.e., Bluetooth) to save space on the primary board. The system required a dedicated 4W power output comprising a power MOSFET controlled by a processor with a fuse for on skin safety, and small-gauge connection points for attachment to the heating elements.

3.3 Survey

The online survey consisted of (1) a pre-survey and (2) a main survey (Figure 3) requiring 30 minutes for completion. The pre-survey consisted of a questionnaire covering demographic data and a survey question to gauge the participant's understanding of on-skin devices. After viewing a short clip of an on-skin device operating on the inner forearm, participants were asked to select

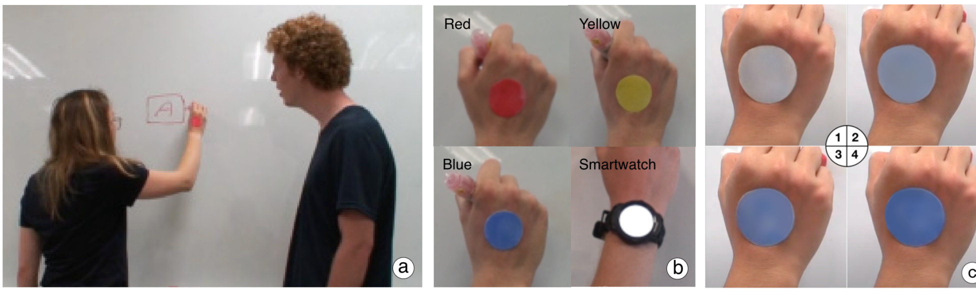

Fig. 4. Example frames from videos used in the online survey, showing the overall scene and closeups of the wearable devices. (a) A female wearing an on-skin device, the color of which changes to red when a notification is received. (b) Closeup of a smartwatch and an on-skin device when a notification is received. (c) Progressive color-change (from white to blue) of the on-skin notification device.

statements that represented their understanding of the device. Only those who selected the correct statements proceeded to the next stage.

The main survey began with videos depicting male and female actors interacting with on-skin devices attached to the back of the actor's hand. The device gradually changed from the base color (e.g., white) to one of three final colors (red, yellow, or blue) when a notification was received (Figure 4b). Figure 4c presents four snapshots of an on-skin device going through the gradual color change from its base color (white) to an exemplar final color (blue). To avoid distracting the viewers with the board and wire, we modified the display to include only the on-skin overlay. We chose the back of hand as it was easy to reach and not covered by clothing. The back of hand is also the selected placement by current commercialized on-skin displays (i.e., LogicInk [5] and L'Oreal My UV Patch [12]). A smartwatch (TicWatch E2 [9]) with a lighted screen was also shown and rated by participants to serve as a baseline score of what is currently considered socially acceptable. All three colors and the baseline case were included in the presentation. We used two sets of actors, one from the US (for US participants) and one from Taiwan (for Taiwanese participants). This resulted in a total of 16 video interactions. The videos were shot from a distance of 2 meters to capture the entire scene as well as in closeup (30 cm) to focus on the color-change process. The clips were edited to include an overlay description indicating that a notification was received just as the color-change process began (Figure 4a). Following the completion of the clip showing the entire scene (35 seconds), each of the closeup clips respectively looped once (10 seconds). The video sequences were randomized in terms of color and gender.

After the participants viewed the videos, they were asked to complete a follow-up questionnaire probing their global perceptions of the color-changing on-skin display. The questions were drawn from You et al. [76] and Profita et al. [57]. The participants were asked to identify the color they preferred to be displayed on the on-skin interface (they were asked one question about their preference for RYB, and a second question that allowed them to choose any color). The participants were also asked to rate their preferences related to notification speed and duration, and select the types of applications for which they would like to receive notifications.

3.4 Semi-Structured Interview

Our objective in conducting in-lab semi-structured interviews was to gain deeper insight into the perception of color changes on on-skin displays. The interview study consisted of (1) a pre-study phase, (2) a material probe phase, and (3) a post-study interview (Figure 5). Unwanted shadows

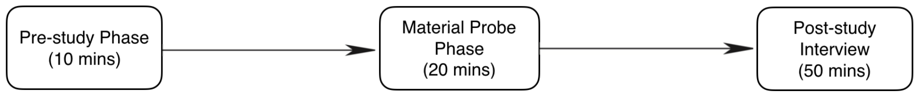

Fig. 5. In-lab semi-structured interview protocol.

influencing the color display of the on-skin device were eliminated using a makeup lighting system for non-flickering, natural illumination of the device and surrounding environment. Throughout the interview, the participants sat in front of the makeup lighting station with a white backdrop to prevent color interference.

3.4.1 Pre-Study Phase (10 minutes). Participants were asked to share their general perception of the three primary colors. The participants also tried on the smartwatch and were asked about their opinions related to smartwatch notifications. The pre-study results served as a baseline from which to compare the experience of wearing a color-changing on-skin display.

3.4.2 Material Probe Phase (20 minutes). The *SkinDisplay* device was first placed on a table and activated to change from the default color (white) to a destination color and then revert to the default. Participants were encouraged to touch and observe the device. The SkinDisplay was then affixed to the participant's dominant hand, and wirelessly activated. After allowing the participants to experience the on-skin color change, they were asked to talk about notifications that they envisioned to receive from the device. Finally, the SkinDisplay device was activated a second time, during which the destination color was randomly assigned among the three primary colors.

3.4.3 Post-Study Interview (50 minutes). We conducted a semi-structured interview to understand their perception towards the on-skin display. The questions dealt with (1) the participant's opinions as to the design of the on-skin displays, including the material, pattern, shape, size, and color of the device; (2) their opinions related to the design of notifications, including notification speed and duration; (3) the applications they would prefer to connect to the notification system; (4) concerns related to wearing the *SkinDisplay* device on a daily basis; (5) examples of existing technologies or real-life experiences that reminded the participants of wearing an on-skin notification device; and (6) envisioned usage scenarios.

3.5 Analysis

Independent samples t-test (Chi-squared test) were used to compare the means of age, gender, and education level between the US and TW groups recruited in the first-stage (survey) and second-stage (interview) of the study.

Audio recordings of the semi-structured interviews were manually transcribed to identify salient themes. All qualitative data (including the responses to each open-ended question in the first-stage and each transcript of interview responses in the second-stage) underwent iterative coding, which was conducted independently by three experienced researchers. Then, all of the authors discussed the meaning of the text to identify common themes. In both stages of the study, we used codes with a reasonable degree of agreement among the coders to identify salient themes based on thematic analysis [71].

4 RESULTS

In this section, we summarize the results collected during the survey and interviews.

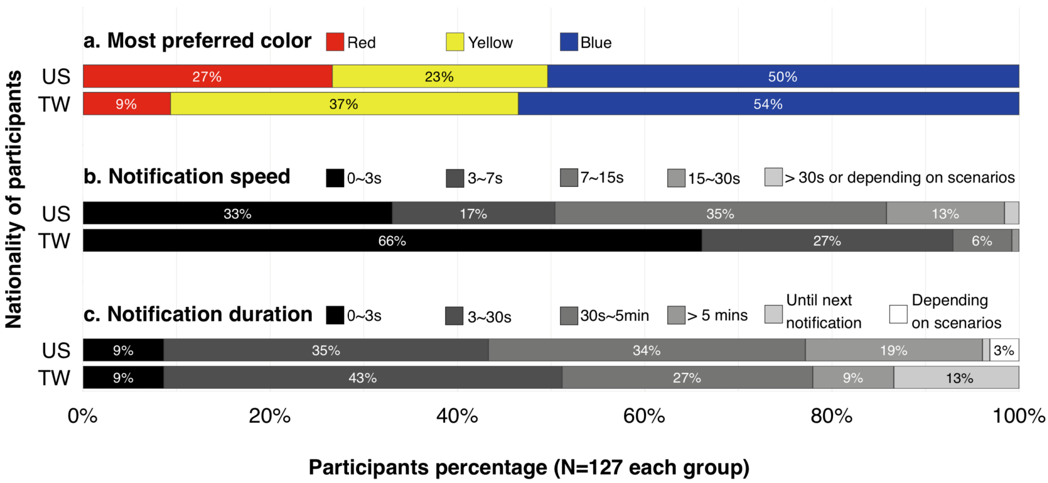

Fig. 6. Preferences of participants in the US and TW online surveys: (a) preferred display color, (b) preferred speed when a notification arrives, (c) preferred notification duration before changing back.

4.1 Survey Results and Observations

The survey probed participant attitudes towards the color-changing on-skin display. Figure 6 summarizes their preferences towards display color, notification speed and duration, applications connected to the notification system, and comparison with existing body-worn form factors, which we described as follows.

4.1.1 Notification Color Preference. Participants were asked to rank in order of preference the notification colors presented in the video clips. Blue was selected as the preferred color by participants in the US and TW (US: 50%, TW: 54%) (Figure 6a). The US participants selected red as their second choice (27%) followed by yellow (23%). The TW participants selected yellow as their second choice (37%) followed by red (9%). US participants described blue as "calm" and "neutral." They said it was the least "jarring/distracting" and was noticeable without causing the discomfort of red and yellow. They also noted that it contrasted against their pale skin tones without looking like a diseased skin condition. The Taiwanese participants described blue as more gender-neutral, but selected yellow as their second choice, due to the way it blended in with their skin tones. The Taiwanese participants also described the red as a feminine color.

Participants also used an online color picker [4] to select their preferred color beyond the three primary colors. The color codes were mapped to approximate color regions in the CIE chromaticity diagram (as shown in Figure 7) [23]. The US participants selected pink (1%) as their preferred choice followed by blue (7%), white (7%), and reddish-brown. Taiwanese participants selected white (11%) as their preferred choice followed by purplish-blue (6%), and blue-green (5%).

4.1.2 Notification Speed and Duration. Participants were asked to specify preferences towards the notification speed ("How long should it take for the notification to change from colorless to the final color?") (Figure 6b). Participants could choose from among the following responses: "within 3 seconds," "between 3 and 7 seconds," "between 7 and 15 seconds," "between 15 and 30 seconds", or "more than 30 seconds". Most US participants (50%) preferred that the notification process be completed within 15 seconds, whereas most Taiwanese participants (66%) preferred that the process be complete within 3 seconds.

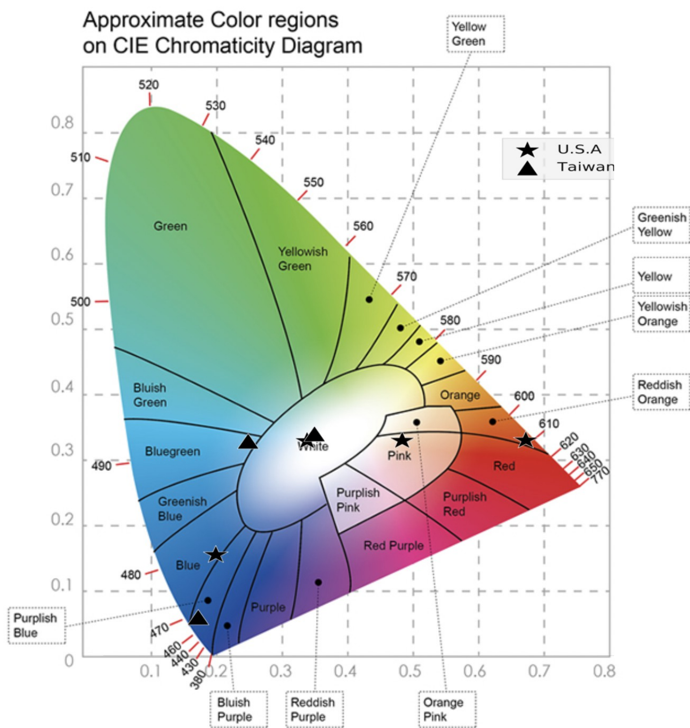

Fig. 7. Top-three colors preferred for notifications (not limited to RYB) selected by US participants (stars) and TW participants (triangles) mapped in approximate color regions shown on CIE chromaticity diagrams [23].

Participants were also asked to specify preferences toward notification duration ("How long should the final color be displayed on the on-skin device?") (Figure 6c). Participants could choose from among the following responses: "within 3 seconds," "between 3 seconds and 30 seconds," "between 30 seconds and 5 minutes," "more than 5 minutes," or "last until the next notification is received." More than half of the US participants (53%) preferred the final color to stay on the device for longer than 30 seconds or until the next notification is received. Most TW participants (52%) preferred the notification duration to end within 30 seconds.

4.1.3 Applications Connected to Notification System. Participants selected the type of applications for which they would like to receive on-skin notifications (Figure 8). The options include "system notifications," "social networking," "productivity," "news," "entertainment," "health," "business," "finance," "education," "lifestyle," and "other." Among US participants, the most popular apps were those to related social networking (e.g., Facebook, Instagram, or LinkedIn) (57%), followed by apps related to health, wellness, and fitness (54%) and system notifications (47%) (e.g., software updates or low battery). Among TW participants, the most popular apps were also those related to social networking (83%), followed by system notifications (75%), and productivity apps (69%).

4.1.4 Comparison with Existing Body-Worn Form Factors. Nearly half of the participants in the US (45%) and Taiwan (47%) mentioned that the proposed color-changing device reminded them of existing wearable devices, such as smart-watches and earpods. The US participants also compared it to body art or tattoos (28%), medical-related devices (24%), and on-skin stickers (5%). The Taiwanese

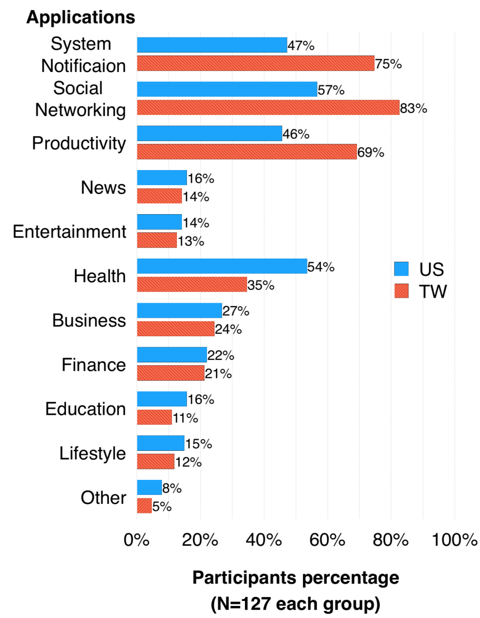

Fig. 8. Applications for which participants would like to receive on-skin notifications.

participants also compared it to medical-related devices (21%), accessories (17%), and body art or tattoos (16%).

4.2 Semi-Structured Interview Results and Observations

We conducted a semi-structured interview involving 36 participants (18 Americans and 18 Taiwanese) to gain a deeper understanding of how cultural norms influence user perceptions of notification devices. In the following, we report on the qualitative results obtained from these semi-structured in-lab interviews.

4.2.1 Shifts in Color Perception When Worn on the Skin. The perception of many colors changed from neutral/positive to negative when the device was applied to the skin. All US participants (N=18) and twelve TW participants (T02–T03, T05–T06, T08–09, T11, T13–T16, T18) described a shift in perception.

> *"On the white table the colors looked very nice. On the skin, there's hair, there's freckles, there's weird veins and things like that, so I enjoy them less on the skin than I do in the abstract. They are too intense, monochromatic, and less organic on the skin. Though when the notification is off and they are white, they have a little bit of texture to them and are less obtrusive."* — (U02)

More specifically, this shift in perception is often associated with skin conditions. Yellow was singled out by seven US participants (U01—U04, U06, U10, U18).

> *"What do you think about the color yellow?] Yellow is warmer than blue but colder than red, it's sunny and happy... [What about wearing it on your skin?] Yellow isn't the best color on my skin, it reminds me of jaundice."* — (U02)

Among the participants who described the perception shift, four US participants (out of eighteen), and six TW participants (out of twelve) attributed a cultural association toward a color.

> *"[What do you think about the color red?] Red is a more pronounced and lively color, it makes me think of the Lunar New Year, and of course, red envelops... [What about wearing it on your skin?] It looks like I'm bleeding!"* — (T13)

In some cases, participants noted cultural connections after the device was worn on the skin:

> *"[What do you think about the color blue?] It reminds me of technology. It is a very reliable color. [What about wearing it on your skin?] Blue on the skin reminds me of livor mortis, you know in science fiction manga, the skin turns blue after the person passes away..."* — (T03)

4.2.2 Scenario Specific Preferences for Wearing the Device. Several participants in both countries mentioned family gatherings and meals as specific scenarios in which they would not like to wear the device. Eight US participants (U05—U06, U08, U11–U13, U15–U16) mentioned the importance of not wanting to be disturbed during family time, but only two TW participants (T09, T13) cited this as a concern.

> *"Because [...] you want to spend time with your family... I don't need to be reminded of the outside world... If it's a big, big emergency then we'll probably know it anyways."* — (U05)

Eight TW participants reported not wanting to use the device during family gatherings to avoid questions from senior family members (T02—T04, T08, T10, T12–T13, T15).

> *"When I went back for dinner, sometimes my grandfather asked me what I was wearing or why I wanted to wear this. But people from an older generation don't follow technology trends closely, so they don't appreciate it even if you explain in great detail."* — (T04)

For family gatherings, TW participants preferred wearing yellow (T04, T18) or a lighter less conspicuous color (T10).

4.2.3 Design Consideration Shift. Device Functionality vs. Personal Expressiveness. The US and TW participants differed in their preferences towards the color and graphical design of the device. Eight TW participants (T01, T05, T07, T09, T11, T13, T15, T18) preferred limiting the device to one color. They did not want to wear a "weird pattern" and gravitated towards simplicity.

> *"[Would you prefer a different graphical design?] No, I don't think I want to have a pattern on the device. I want to keep it simple... That is, to display color throughout the entire device area."* — (T07)

Thirteen TW participants (T01, T03–T05, T09–T16, T18) expressed a preference for a more "practical" design for daily use. Among the thirteen participants, eight preferred a circular shape for a compact and smooth design. When worn on the back of hand, they felt that other shapes (e.g., long rectangle), which covered a larger skin area, would drag their skin when they clenched. The remaining five participants preferred a strip/ring design similar to a smartwatch, so that they need not worry about the device when engaging in everyday activities.

> *"I am wondering if the device might easily fall from the skin. I mean ... a smartwatch has a belt that you can wrap around your wrist. There is a clasp keeping it from falling off [...] Honestly, I felt very insecure about the device attached to my skin as a patch [...] I would prefer to have the device designed as a strip, which can wrap around my wrist to ensure it doesn't fall off."* — (T15)

Conversely, eleven US participants were eager to give the device a particular graphical appearance. They expressed a strong preference to wear a unique device as a form of self-expression.

> *"A cool custom pattern that I could choose, such as a neat arabesque or paisley, a cool wavy pattern or picture of a dragon that I couldn't see unless I got a notification then it would emerge. That would look good on my wrist."* — (U12)

Ten US participants (U02, U04, U07—U09, U11, U13—U15, U18) preferred a circular design (N=5; U07, U08, U11, U14–U15) or a strip/ring design similar to a smartwatch (N=5; U02, U04, U09, U13, U18). Unlike their TW counterparts, US participants were less concerned about the practicality for daily use and wanted to express themselves through the device.

> *"Especially if it is on the skin, it reminds me of a temporary tattoo, or like a tattoo you can choose to take on and off, especially if it's really pretty and designed well and people want to wear it almost as a fashion statement. Maybe that's half the reason why people wear watches is because of how they look. Anyway, you could put this wherever you want, and that could be a personal expression. I like how it's organic and not an even color change. I think that's actually pretty cool."* — (U08)

4.2.4 Impact of Lifestyle on Notification Speed. The color of the device can transition instantly or gradually when indicating a notification. The US and TW participants differed in their preferences. Thirteen TW participants (T01–T02, T04, T06, T08–T10, T12—T17) preferred that the device change from colorless to the destination color within three seconds, similar to the instant feedback associated with conventional mobile notifications. TW participants reported that a more gradual transition would not fit with their fast-paced lifestyle.

> *"I would like the device to undergo a noticeable color change at a specific point in time. The whole point of setting a reminder is to get to the task immediately after I get the notification. However, if I saw the device gradually changing its color ... I would not be able to tell if I should respond immediately or wait for it to change?"* — (T15)

Fewer US participants (N=7; U01, U07—U08, U11—U13, U17) preferred an instant color-change and one did not express a preference. Ten US participants (N=10; U02–U06, U10, U14–16, U18) reported a preference for a subtle (i.e., less obtrusive) notification, which felt more "organic" and "connected" to their bodies.

> *"It's organic and it looks kind of nice. The way it changes color is a bit slow, but I like the analog quality of it. I appreciate that it's not binary with only an on or off state, but rather presents a gradual color-change."* — (U02)

4.2.5 Association between Colors and Notifications. The participants in the two countries differed in their associations with the three primary colors (or other preferred colors): Sixteen TW participants (T01–T14, T17—T18) expressed a preference to prioritize target events (e.g., crucial, important, and trivial) and assigning salient colors accordingly.

> *"[What kind of notification would you want to receive in the three colors?] Red gives me a sense of urgency. At my workplace, I would see red as an indication of an overdue official document. I would assign the other colors [i.e., yellow and blue] according to the priorities of the events."* — (T06)

Eight US participants (U02–U03, U06, U09–U11, U13–U14) associated the colors metaphorically, such as red as a metaphor for blood (i.e., health-related events) or blue as a metaphor for water (i.e., time to hydrate).

> *"I would choose the blue notification to remind me to hydrate. A yellow notification could be related to UV or sunlight exposure. Red reminds me of my blood pressure rising or something, so cardiovascular stuff like walking. The green would be for money or bank account notifications. The American dollar is green."* — (U09)

4.2.6 Cultural Aspects of Color Perception. Participants in the two countries differed in their perceptions of color. Eleven TW participants (T01, T03—T08, T11, T15—T16, T18) disliked the color purple, while only three US participants reacted negatively to it (U03, U08, U18). T04 and T06 described purple as "unsuitable for placement on the human body." Some of the negative connotations to purple were related to Taiwanese media culture:

> *"In animations, the color of the aura surrounding villains is usually purple [...] Whoever absorbs this aura, something bad would happen to them. Also, purple is often an indicator of poison..."* — (T08)

Five US participants (U04, U09–U10, U17—U18) expressed a distaste for wearing orange on the skin, while only one TW participant expressed the same concern (T05). US participants had concerns that orange adversely complemented their skin tone.

> *"I dislike orange just because I don't think it goes well with my complexion and skin-tone. I also feel that orange clashes with my hair... also, many prisons in the US have orange jumpsuits. It is also a color that signifies that someone should be alert, such as in construction vests, caution, and hazard signs."* — (U17)

5 DISCUSSION

The results obtained in this study identified two key factors influencing user perceptions of color-changing on-skin displays: cultural overtones and the need to match colors to skin tones.

5.1 Revisiting Cross-Cultural Psychology For On-Skin Color Perceptions

Our studies yielded several cross-cultural differences between US and TW participants. Psychological experience (at the individual level) [27, 78] is not the only mechanism that affects our perception of color. Cultural factors, such as language, cultural norms, values, and taboos, also play a role in shaping our perceptions [28, 63]. Shweder et al. [64] defined culture as shared elements that "provide the standards for perceiving, believing, evaluating, communicating, and acting among those who share a language, a historical period, and a geographic location." Some previous cross-cultural studies of color perception [10] reported that these shared elements reveal stable cross-cultural similarities. For example, red is widely viewed as an alert whereas black and gray have negative connotations. In the current study, US and TW participants both viewed red as "exciting" and "passionate".

Besides cross-cultural similarities, there are *culture-specific perceptions* towards the design of on-skin notification devices, which are shared within a specific country and are influenced by a variety of cultural factors [48, 78]. In this study, US and TW participants both described culture-specific color associations. The neutral association T03 had with the color blue changed to negative when worn on the skin due to associations with livor mortis in manga animations popular in Taiwanese culture (Section 4.2.6). Campbell et al. [14] observed that people from Western societies tend to be more engaged in self-expression than their Eastern counterparts. This difference in cultural orientation (i.e., individualism-collectivism difference [14, 26]) was reflected in the emphasis US participants placed on using the device for self-expression, as opposed to the functionality and practicality preferred by TW participants (Section 4.2.3).

Design Implications. Clearly, cross-cultural psychology can be used to elucidate the perception of individuals toward on-skin displays. With the evidence collected in our survey and interviews, we have empirically demonstrated that the perceptions of individuals toward these notifications differ across cultures. Designers and device manufacturers should consider the cultural mechanisms underlying the perceptions of potential users in the design of devices that are specific to a particular group or meant to span multiple demographics.

5.2 Impact of Skin tone in the Design of On-Skin Displays

Compared to other wearable display form factors, on-skin devices are particularly sensitive to the issue of skin tone. The Taiwanese participants in this study selected blue as the preferred primary color due in part to the way it contrasts with their skin tones. T06 (with a medium skin tone) made the following comment: *"Blue had the best color contrast with my skin. If I want the notifications to catch my attention, then I feel fine with the blue on my skin. [...] Compared to red, blue is more low-key."* Other Taiwanese participants with medium or medium-dark skin tones (N=13) selected yellow as the best color for their skin. T15 (medium skin tone) made the following comment: *"I feel yellow is the most suitable color to put on the skin. First, the skin color of a Taiwanese person like me is relatively yellow. When I wear yellow, it is not as obvious as red or blue and looks softer. I feel it is more friendly and more acceptable to others."*

Many of the US participants in our lab experiment (N=11) had fair or light skin tones. For such people, the ruddiness of their complexion is well-suited to the color red (see Figure 9a top row for an example). U08 (light skin tone) made the following comment: *"I like [the red device] because there are more red tones in the skin than blue, and I like that it is not too noticeable and compliments my skin tone."*

Nonetheless, it is important not to disregard individual preferences, which often differ from general trends. T16 (medium skin tone) made the following comment: *"Among these three colors [i.e., red, yellow, and blue], blue is the most obtrusive. I feel the blue color is very different from my skin color ... I mean, there is no human with this kind of skin tone. I think I would keep looking over at the person who wears the blue color and wondered why he picked this color. Although this blue color is my favorite, I would not pick this one to put on my skin."*

Design Implications. Skin tone is an important issue in the selection of wearable accessories, such as smartwatches; however, sensitivity to this issue is heightened when dealing with on-skin displays. Thus, helping potential users to evaluate the colors associated with on-skin displays on their skin could go a long way toward making the devices more acceptable/desirable. This could be done by providing a reference dataset containing photos of people with different skin tones wearing the on-skin display (see Figure 9). This approach is widely used in the cosmetics industry for the display of makeup colors. Note that on-skin devices straddle the distinction between wearable devices and body art (see Section 4.1.4), which suggests that they could be treated as a form of cosmetic or decorative accessory.

5.3 Screen or Canvas? Wearable Materiality Perceptions Across Cultures

This section considers the characteristics of the materials used to create on-skin displays. Most people agree that materials worn closer to the body (e.g., textiles) should appear natural. Thus, it is not surprising that there has been a shift from digital to analog displays using non-emissive materials interwoven into the structure of the textile. Early on in the exploration of textile displays in the late 1990s, e-textile pioneer Maggie Orth predicted that digital "LED" displays would not reach broad acceptance due to their "rave-wear"-like aesthetic [61]. There has been extensive research into thermochromic textiles [1], which present a gradual morphing quality. In 2016, Devendoft et al. [20] reported that most people would prefer not to wear a (digital) screen, but found the analog aesthetic of thermochromic textiles appealing. In a 2017 study on analog powder-based on-skin displays, Kao et al. [34] observed positive reactions towards gradual, analog color change qualities resembling body art. Note however that all of the above-mentioned studies were conducted in the

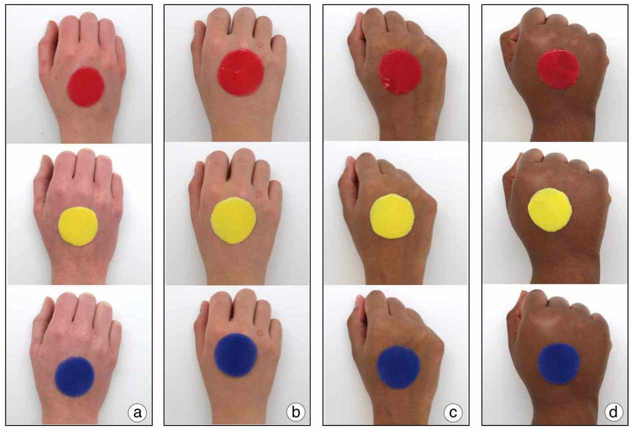

Fig. 9. Red, yellow, and blue on-skin overlays as they appear on different skin tones: (a) Fair (b) Medium (c) Dark (d) Deep.

US. The Taiwanese participants in the current study expressed a strong affinity for faster changing, digital-like displays. Their preferences were less rooted in aesthetic concerns as in practical matters; i.e., "communicate what is needed as soon as possible." Note also that in the surveys and interviews, US participants expressed a desire to use on-skin displays for health-related notifications, whereas TW participants were more concerned with work-related notifications. This may be explained by the extreme density and high pace of Taiwanese society, with a culture of long work hours and relatively little concern for work-life balance.

Design Implications. As reported by du Gay et al. [21], the meaning of worn objects is complicated and intrinsically tied to culture. It is therefore not surprising that we found differences between the two groups in this study in their perceptions of on-skin designs. We suggest that further research based on cross-cultural methods be used to examine perspectives beyond a single culture.

6 LIMITATIONS AND FUTURE WORK

This study involved an online survey and lab experiment in a controlled setting. Conducting field experiments in a natural setting could increase ecological validity and reveal under-explored scenarios for interactions. This study focused on a single on-skin display and its output interactions (i.e., changing the device color to notify users when receiving a notification) in order to reach a larger number of participants by limiting the time required for participation. We also limited the analysis to three representative colors and placement on the back of the hand (mirroring placement of the smartwatch). Future research could investigate participant attitudes towards a broader range of design factors, including device color, placement, on-skin form factors, interaction modalities, and demographic factors.

Note also that the prototype used in the semi-structured interviews required a connection to external hardware and battery components (a common limitation of current on-skin interfaces [37, 73]). The device was also limited to a single color (i.e., one-bit). Future design efforts in the area miniaturization could lead to the development of autonomous devices with sophisticated displays and long-term deployment.

7 CONCLUSION

This paper presents a cross-cultural examination of user perceptions pertaining to a color-changing on-skin display device. The first stage involved an online survey to probe first-person perspectives, and the second stage involved a lab experiment using an actual *SkinDisplay* device as a material probe to elicit first-person perspectives. Semi-structured interviews were used to gain deeper insights into the potential usage of the device and its overall appearance. We identified a number of culturally-sensitive concepts applicable to the design of on-skin displays, such as the heightened importance of color in relation to the skin tone of users, and preferences towards the materiality and speed of notifications. To the best of our knowledge, this is the first study to examine societal perceptions of on-skin color-changing displays. As on-skin wearable displays become increasingly miniaturized, it will be necessary to uncover user attitudes in tandem with device development in order to create on-skin interfaces that are not only highly functional, but also considerate to broader social and cultural sensitivities.

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