EarthTones: Chemical Sensing Powders to Detect and Display Environmental Hazards through Color Variation

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CHI'17 Extended Abstracts, May 06-11, 2017, Denver, CO, USA
© 2017 ACM. ISBN 978-1-4503-4656-6/17/05…$15.00
DOI: http://dx.doi.org/10.1145/3027063.3052754

Abstract
We present EarthTones, cosmetic-inspired wearable chemical sensing powders to detect and display harmful environmental factors through color change. We seek to create an analog display experience through chemical reactions that overcome current constraints of rigid, battery-laden wearable displays. We designed three unique chemical changing powders to reflect elevated levels of carbon monoxide (CO), ultraviolet (UV) rays, and ozone (O_3). The powders achieve color changes distinguishable to the human eye, while maintaining an aesthetic appeal to the wearer. Our technical evaluations confirmed the performance of the powders to detect and display elevated levels. An 18-person exploratory study provided insight to the perceptions, possibilities, and challenges of a powder form factor for wearable environmental visualization. Through this paper, we intend to enable the use of colorimetric chemical displays for HCI researchers and designers. More generally, we seek to encourage the research and use of chemical-based sensors and interdisciplinary research in HCI.

Figure 1: EarthTones is a wearable chemical display in the form of cosmetic powders. It senses environmental pollution, and generates color change to display hazardous levels. We created three powder instantiations which detect carbon monoxide (CO), ultraviolet (UV), and ozone (O_3). In the example of an UV sensing powder, a color change from yellow(a) to dark red(c) occurs when exposed to UV.

Author Keywords
Chemistry; on-skin interface; makeup; wearable computers; environmental sensors;

Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

Introduction
How much harmful exposure do we risk every day from invisible environmental pollutants? Whether we are in our homes, out commuting, or simply enjoying an afternoon stroll, these unseen hazards can often go undetected by humans leading to minor symptoms such as nausea, and even fatal diseases such as cancer under prolonged exposure. For instance, long term exposure to CO can result in respiratory problems [30], and UV is linked to increased rates of skin cancer [5]. While there are technologies designed to detect environmental hazards [8,23,35,37,38,41], they still require limited uses of power and electronics (and pairing with phone apps), and entire systems are unlikely worn seamlessly on the body.

For some, applying powders or creams is a daily habitual practice. Whether decorative or medicinal, they seamlessly blend with our bodies when applied, and are designed to be easily removed. Today, people apply powders to protect their skin while enhancing features and covering flaws. Unlike traditional passive powders, we chemically engineer ours to also function as continuous sensors and actuators. We seek to integrate environmental sensing into existing daily practices of wearing body powders, which are already exposed to the environment and visible to the naked eye, rather than adopting an additional device practice.

Researchers have sought to expand environmental detection devices into skin-worn form factors. For example, the L'Oreal My UV Patch [17,26] is a stretchable skin patch which detects and displays UV levels through colorimetric inks. However, it still consists of an electronic layer for wireless communication. In this paper, we seek to explore an electronic-free, seamless wearable experience by coupling sensing and actuation on the molecular level, creating a *powder* form factor which detects and displays three types of environmental hazards: CO, UV, and O_3 exposure through granular color change, creating an analog display. We are exposed to these three environmental hazards daily at low levels, often unaware of their health effects upon long-term exposure. Subsequently, these powders were designed to reflect cumulative exposure levels throughout day (8 hours worn) that over time are harmful but not acutely deadly to the wearer to increase awareness. They were not designed to be instant notifications of acute levels, but instead present a gradual spectrum change to mirror gradual exposure levels.

To enable a wearable chemical display, a few design themes must be met. First, sensing and actuation must be coupled into a powder form factor. To achieve this level of granularity, there is a need to move beyond electronics and into the molecular level, which calls for interdisciplinary HCI research into chemical engineering. Second, as a wearable display, it must achieve color changes distinguishable to the human eye such as saturation, opacity, and spectrum. Third, it must be appealing and easy to wear. The colors should resemble the aesthetics of commercial body powders. It must also be customizable to the wearer's skin tones and personal aesthetics, so wearers can easily integrate it with their everyday dress. The application and removal should be simple and straightforward.

While colorimetrics and environmental sensing have been explored in chemical engineering, to the best of our knowledge there is no device in the HCI or chemistry literature which achieves a wearable display in a powder form factor. We present EarthTones, a wearable chemical display, initiating an exploration from Human *Computer* Interaction to Human *Chemical* Interaction.

The contributions of this paper are as follow:

- We developed wearable chemical displays in a powder form factor, presenting three instantiations: (1) CO, (2) UV, and (3) O_3.
- Technical evaluations of the performance of the developed chemical displays.
- 18-person exploratory study to unpack user perceptions and application possibilities for a wearable chemical powder system.

Background and Related Work

Wearable displays

In recent years, we have witnessed a rise in wearable displays in many forms: from head-mounted [15,31,32], wrist and finger worn [3,4,33], projection-based [6,7,14], to LED-laden textiles [11]. These digital displays are fast, precise, and high-resolution. However, they are often constrained to the rigidity of display electronics and battery life. While there have been efforts to evolve digital displays closer to the human body [36,42], we observe an emerging trend moving towards *hybrid displays* which are partly chemical and partly electronic in composition.

Hybrid displays
Unlike their digital predecessors, hybrid displays leverage both digital and natural (i.e., chemical) means to achieve actuation. Typical response time is often slower and resolution tends to be cruder, but they leverage textures in more meaningful ways [27]. However, they still require a layer of electronics for actuation or communication. A representative example is L'Oreal's My UV Patch [17,26] which is composed of photosensitive inks encapsulated in thin silicone. The patch changes color when exposed to UV rays and is equipped with an NFC antenna in a layer below for wireless communication. Thermochromic displays [13,18,19,24,27,29,34,43] leverage pigments which change color when triggered by an underlying layer of resistive heating circuitry. This includes textile displays [13,24,27,29,34,43] which coat thermochromic pigments onto fabric or threads to create color changing textiles, and thermochromic skins [18,19] which layer thermochromic pigments on tattoo paper to create soft, skin-conformable displays. Other works have explored humidity responsive bacteria as shape-changing biological actuator displays [16,28].

In this work, we move from a *hybrid display*, which is still inclusive of battery and electronics, towards a pure *natural display* consisting of only chemicals: the chemical itself senses input and generates output (i.e., color change) without electronic components (Figure 2). This enables form factors even more intimate to the human body, such as a fingernail-based pH sensor [22]. They also present analog, continuous color change which resemble body art aesthetics. Our work presents a manifestation of a *natural display* in an underexplored *powder* form factor.

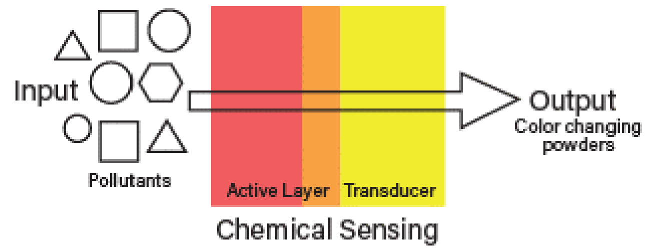


Figure 2: How a chemical sensor display works

Environmental detection fashion
Given the growing concerns around climate change, the fashion and wearable community has explored visualizing unseen environmental data through clothing. The Climate Dress [9] is laced with hundreds of LEDs that respond to CO_2 levels with an integrated CO_2 detector. Aerochromic Shirts [1] are printed with radioactive sensitive dyes which reveal patterns upon exposure. The Unseen Group [40] created a series of chemically reactive garments and accessories that change color when exposed to heat. WearAir [39] presents air quality through clothing embedded LEDs. These visualizations, however, are either sensor laden or not technically quantified. In line with these works to reveal invisible environmental hazards through means of fashion, EarthTones explores a novel powder form factor that is also technically evaluated for seamless body integration and wearability.

EarthTones Prototype

Theory of Operation for Human Chemical Interaction
To achieve a powder form factor, sensing and color actuation is coupled into the molecular level though

chemical engineering. In human *computer* interaction systems, which are mainly hardware driven, the microprocessor is the brain of the system which detects input and in turn actuates output. A human *chemical* interaction, on the other hand, is driven by a two-component system: the active component senses *input* (e.g., environmental pollutants), whereas the transducer component activates a corresponding *output* color change. In many cases, the two components are coupled in one chemical reaction. We focus on the sensing of three environmental pollutants: CO, UV, and O_3, which each generate independent color changes. Below, we elaborate on each prototype, and also evaluate the performance.

1. Carbon Monoxide (CO)

CO is an odorless, colorless, and tasteless gas which can occur indoors due to leaky appliances fueled by natural gas, or outdoors due to vehicle exhausts and coal burning systems. When inhaled, CO displaces the oxygen in the blood stream, disrupting normal respiratory function. 50ppm (parts per million) [10] is the maximum permissible exposure level in workplaces. Exposure beyond 100ppm after 1-2 hours can cause headaches, and levels beyond 400ppm can be life threatening after 3 hours.

Design Goals. To create a saturation color change to reflect exposure levels above 50 ppm, we referenced the chemical reaction of CO detection cards [44], which trigger a yellowish to dark brown color transition. However, as this color response was not aesthetically pleasing, we built on this base reaction and formulated our own chemical compounds through iterative testing to achieve body powder aesthetics.

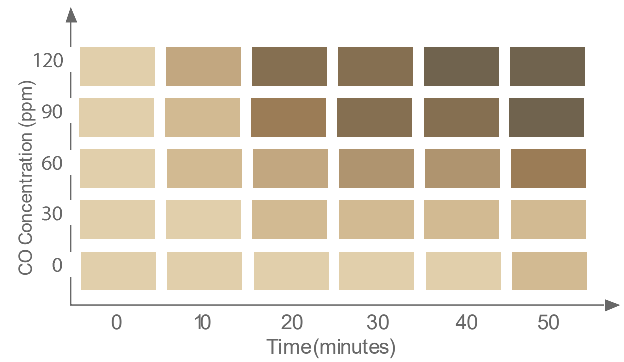


Figure 3: Color response of CO powder

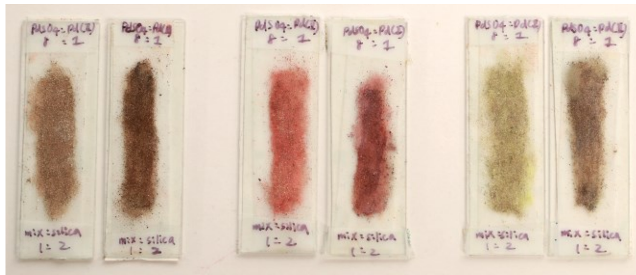
Implementation. Our prototype CO sensor takes advantage of the oxidation of CO to carbon dioxide (CO_2) by a palladium(II) complex (Scheme 1). In this reaction, $PdSO_4$ is embedded in silica in a 1:2 gram ratio resulting in a tan color. The Pd(II) species oxidizes the CO to CO_2 and is reduced to a Pd(0) species which is black (Figure 4a).

$$Pd^{II} + CO \longrightarrow Pd^{0} + CO_2$$

Scheme 1: The chemical reaction of CO and Pd(II)

Results. We evaluated the CO powders by measuring the color change as a function of both CO concentration and time (Figure 3). Thin films of the CO powder were exposed from 0-120 ppm of CO in 30 ppm increments over 50 minutes. At a safe threshold of 30 ppm, the CO sensor had little color response, whereas above 60 ppm, the sensor response was clearly visible with an onset time of 20 minutes.

The overall color characteristics of the sensor were tuned by addition of various pigment to achieve desired



Before | After Before | After Before | After

Figure 4: CO sensors with different pigments

shades. Figure 4 presents various pigment mixtures to create different makeup tones, from silver to red earth tones.

2. Ultraviolet (UV)
Ultraviolet light is an invisible form of electromagnetic radiation that has a shorter wavelength and higher energy than visible light. It can break bonds between atoms in molecules; mild exposure can cause sunburn, while prolonged exposure can alter DNA molecular structures and can cause skin cancer.

Design Goals. To achieve a spectrum color change to reflect UV exposure levels throughout the day, we experimented with both commercially available photochromic powders and alternative methods in the literature. Photochromic powders [12] are easily accessible off-the-shelf, but change color instantly and are not able to serve as a continuous indicator. Mills et. al.'s method, on the other hand, triggers an acid release upon UV exposure, and in turn generates a gradual color change in the pH-sensitive dye [2]. We experimented with combinations of various photosensitive acids and pH-sensitive dyes before arriving at our own chemical formulation for an aesthetic response.

Implementation. The UV sensor consists of two separate components: the active layer is a photoacid (UVAH) that absorbs UV light and generates acid (H^+) proportional to the amount of light absorbed. The acid released reacts with the pH dye (transducer layer), causing the dye to change colors (Scheme 2). The onset time prior to color change is modulated by addition of a base that acts as an acid buffer.

$$\begin{aligned} \text{UVAH} &\longrightarrow \text{UVA}^- + \text{H}^+ \\ \text{Dye} + \text{H}^+ &\longrightarrow \text{DyeH}^+ \end{aligned} \qquad (2)$$

Scheme 2: The principles behind UV sensor

For the prototype, we employed diphenyliodonium chloride (DPIC) as the UV photoacid generator, thymol blue (TB) as the pH-sensitive dye, and sodium hydroxide (NaOH) as the base A solution was prepared by dissolving DPIC and TB in a 1 to 7.5 gram ratio in a 50/50% volume mixture of water and ethanol. To adjust the color change response time, a 0.1 M NaOH buffer was used to adjust the solution to slightly alkaline conditions. To generate a powder form factor, we dried the solution as a thin layer on a glass surface pretreated with dilute aqueous NaOH. Once dried, we scraped off the solid and crushed it into a fine powder.

Results. Thin films of the UV powder sensor were exposed to ambient UV radiation. Films with no UV exposure did not change color, while those exposed 1-2 hours (medium exposure) transitioned to an orange-red hue. The thin powder films exposed 3-4 hours (long exposure) to UV radiation turned a dark red (Figure 5).

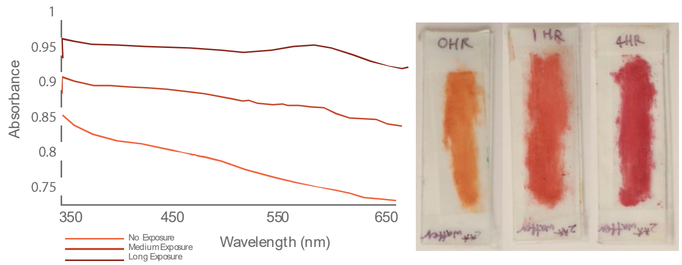


Figure 5: The spectral changes and pictures of thin powder films of the UV sensor before and after exposure to UV.

In addition, the UV powder sensor was evaluated using a Varian Cary 5000 UV-Vis spectroscopy. Thin films of the exposed powders (zero, medium, long exposure) were examined in a spectrophotometer to generate an absorbance spectrum. As the UV sensor is exposed to more UV radiation, an increase in absorbance from 550-650 nm is observed, corresponding to increased orange-red coloration (Figure 5).

3. Ozone (O_3)

O_3 is created typically by chemical reactions between oxides of nitrogen and volatile organic compounds in the presence of sunlight. Breathing ozone can trigger health problems particularly for people who have lung diseases such as asthma. According to OSHA guidelines, ozone levels should not exceed 0.10 ppm for daily exposure. While ozone levels vary based on geolocation, levels can quickly fluctuate in cases of fire, stagnant air and season.

Design Goals. To achieve an opacity color effect from invisible to visible to reflect O_3 exposure levels, we built on the Schoenbein Ozone Test [20] for generating ozone paper test strips. To achieve a powder form factor and aesthetic color response, we formulated our own chemical compounds and integrated makeup tones to achieve a shimmer aesthetic.

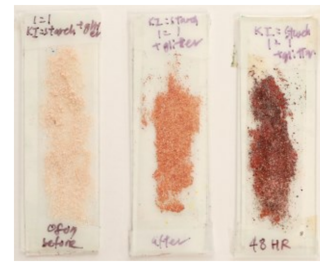


Figure 6: Three stages of ozone exposure

Implementation. The ground-level ozone detector is a two-component system. The first component involves the oxidation of potassium iodide (KI) by ozone to generate iodine (I_2). The iodine reacts with the amylose found in starch. This 1:1 I_2:amylose polymer complex changes the absorption and emission properties of the polymer, leading to a red coloration. The concentration of the iodine present in the complex directly affects the intensity of the color observed, thus providing a measure of the original ozone concentration. Since the color change is irreversible, this system is a good candidate for monitoring exposure over time to the low levels of O_3 present at ground-level.

$$\begin{aligned} 2KI + O_3 + H_2O &\longrightarrow 2KOH + O_2 + I_2 \\ I_2 + \text{starch} &\longrightarrow \text{red/purple complex} \end{aligned} \qquad (3)$$

Scheme 3: The principles behind the O_3 sensor

Results. For the prototype O_3 wearable sensor, we employed this KI/starch system. To evaluate our sensor's ability to detect ozone exposure, thin layers of the powder were placed outside away from direct sunlight. After 4 hours, the original neutral powder turned a peach-tone. After 48 hours, the powder had darkened to a rose red color.

Exploratory User Study

While the area of natural and hybrid skin displays is still in its infancy, it is important to start probing user reactions and envisioned interactions. However, skin safety in relation to these emerging systems remains underexplored; the chemicals used in EarthTones mirror the safety hazards of the L'Oreal My UV patch [17]. However, in lieu of a silicone layer to isolate from skin as compared to the UV patch form factor, we took the most disciplined measures to not expose participants to early forms of these powders. Instead, we simulated the experience by generating a skin-safe prototype with commercial makeup tones which participants apply on skin to infer color response (Figure 7).

We conducted 60 minute semi-structured interview sessions where participants were first introduced to the concept of a chemical powder display and presented with the chemical swatches for observation. Participants were then invited to apply the skin-safe prototype on their skin (Figure 7). They were given the option of using Photoshop to simulate color reactions onto their face. We asked participants to address the context with which they would wear such powders, how they imagined interacting with it personally and socially, how they would read and identify the color change, and how environmental awareness affected their ideas of use. We also frequently presented participants with alternatives to EarthTones that would serve similar functions (i.e, wearable displays and sensors) and asked them to compare and contrast the technologies. All sessions were video recorded and later transcribed for analysis using grounded theory approach [25].

Figure 7: Simulated cosmetic powders for user study.

We screened for 18 participants who wore varying amounts of powders on their bodies, participants included 6 male (aged 27 to 42, M=33), 6 female (aged 26 to 45, M=32) who wore little to no makeup, and 6 female (aged 26 to 44, M=33) who wore medium to heavy amounts of makeup.

Findings

Powder as soft, continuous displays. To our surprise, participants found the analog color change of the powders to be an advantage rather than disadvantage, which echoes the findings of Devendorf et al. [27]'s studies on analog fabric displays. Participants used descriptions such as "continuous", "soft", "blends in with the body" and less "harsh" than a digital display that is "on or off" to illustrate the powders. It was resonant with "makeup, body art aesthetics" and the "ambiguous nature" of the color change left space for personal interpretation which made it "playful" and "layered."

Personalized colors and body location. Most female participants (N=10) described the face as a "public display" and felt comfortable displaying color gradients on their faces as it built on existing habitual practices of wearing makeup. They mentioned the importance of having more diversified colors for individual skin tones and makeup color preferences. Male participants (N=5) preferred the powders to be "invisible" when inactive, and only reveal color change when elevated levels are detected. Participants who did not wear makeup preferred other body areas, such as the arm, legs, or neck for applying the powders. Several male participants (N=3) identified with using the inner arm or wrist as the location for a "private" display as it resembled their watch wearing habits.

Powder as an extensible form factor. The versatility of the form factor enabled participants to "put it anywhere I want." Many participants (N=9) contrasted the powders to the "fixed" form factor of smart watches. We noticed a desire to experiment beyond powder form factors, and to also integrate the powders into temporary tattoos, nail polish, lotions, and creams. Beyond the body surface, participants mentioned applying the powders on jackets, bags, and furniture, and even pets.

Seeing and distinguishing color change. Most participants (N=15) mentioned they were able distinguish the color gradients by eyesight, and did not prefer a phone app for image recognition as it was "cumbersome." Instead, participants (N=6) suggested a temporary tattoo legend to wear next to the powders for comparison. Several participants (N=4) did mention the color changes might go unnoticed when worn on the face, and therefore preferred hands, arms, or other more visible body areas. However, participants who wore makeup regularly said they would notice color changes when checking their makeup through reflective surfaces, mirrors, or smartphones throughout the day.

Discussion and Future Work

Phone app with computer vision algorithms to detect color change. While the results in our user study did not indicate a strong preference to pair the powders with an additional phone app, we see a twofold advantage in providing an optional phone application in future iterations: (1) connecting the chemical-focused work to a *computer* component for greater relevance to traditional HCI, and (2) increased accuracy in color recognition of elevated levels when the powders are worn in the wild. The addition of a phone app with computer vision algorithms could provide automatic calibration under varying environmental conditions (i.e., lightening, time-of-day, etc.) and also adjust for different wearer skin tones.

Software design tool for personalizing individual color tones. Results from the user study reinforced the importance of diversifying for different skin tones and personal aesthetics for increased adoption. To give the wearer ultimate control over the color compositition of the powders, an end user software design tool would assist with the customization of color preferences and then generate the corresponding chemical mixture ratios.

Towards a skin-safe prototype. As the research space of chemical-based analog displays [17] have only emerged since the past year (2016), as in this work, they have focused on the development of working chemical processes, with extensive verification of skin-safety remaining underexplored. The unknown skin safety of the chemicals have limited our user study to initial explorations instead of in depth user studies in the wild, which would be critical for fully understanding user perceptions. A long term future research effort would be to explore skin compatible chemical compositions for a truly wearable experience.

Conclusion

We present *EarthTones*, wearable chemical sensing powders as *analog* display. We created three prototype powders which detect and display CO, UV, and O_3 through color change. Our technical evaluations confirmed the feasibility of the powders to detect environmental hazards. The analog, continuous nature of the displays was appealing to participants in contrast to digital displays, highlighting the skin as a sensitive area for analog style. Through this research, we seek to look beyond rigid, battery-laden wearable digital displays and explore form factors which are malleable, personalized, and enable greater body integration. In the future, we seek to explore further mico-integration and skin-compatible means to create wearable experiences that stem from daily habitual practices of wearing powders and creams.

Acknowledgments

We thank Judith Amores for modeling prototypes, our study participants for their time and feedback, and the reviewers for their insightful comments to improve the paper.

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