ChromoLCD: LCD-based Compact Reprogrammer for On-the-fly High-Resolution Images on Photochromic Surfaces

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Figure 1: (a) ChromoLCD is a compact, high-resolution surface reprogrammer for surfaces treated with photochromic material. ChromoLCD consists of an LCD panel and a backlight with UV and RGB LEDs to achieve high-resolution light patterns at the required wavelengths. ChromoLCD can be used to (b) place reversible tracking markers in the physical environment, (c) stamp custom designs on the user's clothing within minutes, and (d) create high-resolution reference images on a whiteboard that can be augmented.

ABSTRACT

Color-changing materials, such as photochromic pigments, allow objects to have reprogrammable multicolor surface images. Existing systems that reprogram these images are based on projectors and LEDs, each with advantages and limitations in device portability and image resolution. In this paper, we present *ChromoLCD*, a surface reprogrammer that uses a liquid crystal display (LCD) to achieve a compact handheld device without sacrificing image resolution. *ChromoLCD* consists of an LCD panel with a custom backlight containing R,G,B and UV LEDs, forming high-resolution light patterns with the required wavelengths. The compact form factor of *ChromoLCD* enables on-the-fly reprogramming of everyday surfaces. Our technical evaluation shows that ChromoLCD achieves a resolution of 25 ppi, which is 8 times better than the prior work. We demonstrate *ChromoLCD* with three applications, including the stamping of reprogrammable AR markers on a kitchen counter, on-the-fly designs on personal accessories, and reference pictures on a whiteboard.

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CCS CONCEPTS

• **Human-centered computing → Displays and imagers.**

KEYWORDS

personal fabrication; digital fabrication; display fabrication; programmable matter; color change; photochromic

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1 INTRODUCTION

Creating visually dynamic surfaces has been an area of interest in HCI, with applications ranging from product design to integrated displays. Researchers have worked on various methods to achieve visually dynamic surfaces, including optical structures [22, 28] and active materials [9, 10]. Most active materials, such as thermochromic [23] and electroluminescent displays [10], limit the image transition to a predefined set of states. Photochromic material, whose color can be controlled with light, allows for multicolor high-resolution images that can be fully reprogrammed [12].

To create images on photochromic surfaces, researchers have developed optical systems that selectively expose areas of the dye. Single-color photochromic reprogrammers typically saturate photochromic pixels with UV light and rely on ambient visible light to erase the image. For instance, researchers have used UV lasers [2] or grids of UV LEDs [21] to create single-color images on photochromic surfaces.

Multicolor photochromic reprogrammers, on the other hand, require precise control over both the wavelengths and the intensity of the light to individually saturate each color channel. By combining UV and RGB projectors, researchers have achieved reprogrammable high-resolution textures on the surfaces of 3D objects [12, 25]. However, projector-based systems are typically large and require enclosures to block UV light, limiting the portability of the reprogrammer and the surfaces they can be used on.

To improve portability, researchers have turned back to LED-based reprogrammers. For instance, *PortaChrome* [29] achieves this using a hexagonal array of UV and addressable RGB LEDs to supply the required wavelengths, and a custom optical diffuser to align the RGB and UV lights onto the required pixels. The compact form factor of *PortaChrome* enables mobile reprogramming on wearable surfaces, such as a backpack mounted system that can reprogram a user's T-shirt. However, its resolution is limited to 3 pixels per inch (ppi) by the size of the smallest commercially available UV LEDs.

Improving the resolution of LED-based reprogrammer relies on the miniaturization of LEDs, especially at the UV wavelength, which requires decades of industrial research [14]. Even with sufficiently small LEDs, aligning the light from the LEDs of different wavelengths to the same pixel remains challenging. Liquid crystal displays (LCDs) provide a way around this challenge. LCD panels are commonly used in everyday screens, such as computer monitors and phone displays, to map a uniform backlight into high-resolution light patterns through selectively blocking individual pixels. In a photochromic reprogrammer, the LCD panel can create aligned high-resolution light patterns at the four required wavelengths, solving both the resolution and the alignment challenges.

In this paper, we present *ChromoLCD*, the first LCD-based reprogrammer for photochromic surfaces, combining the portability of an LED-based reprogrammer and the high resolution of a projector-based one (Figure 1). *ChromoLCD* consists of a monochromatic 6-inch LCD panel with a custom backlight containing R,G,B and UV LEDs, which yields high-resolution patterns at the required wavelengths. Due to its compact form factor, *ChromoLCD* enables on-the-fly creation of high-resolution reprogrammable patterns on flat photochromic surfaces. *ChromoLCD* has a resolution of 25 ppi and reprograms multicolor images in 15 minutes. We demonstrate *ChromoLCD* with three applications: reprogrammable AR markers on a kitchen counter, on-the-fly design changes on personal accessories, and annotate-able reference pictures on a whiteboard.

In summary, we contribute:

- the first LCD-based photochromic reprogrammer that achieves high-resolution light patterns at the required UV and RGB wavelengths, allowing for creating high-resolution multicolor images on photochromic surfaces while retaining a compact form factor.
- a technical evaluation of the image resolution of the LCD-based reprogrammer, the transmittance and contrast ratio of the LCD panel and the performance on saturating and desaturating each channel of the photochromic dye;
- three applications that showcase the capability of augmenting the physical environment with ChromoLCD, such as reprogrammable AR markers on the kitchen counter, on-the-fly redesign of personal accessories, and high-resolution reference images on a whiteboard.

2 RELATED WORK

We review relevant works on color-changing materials systems, fabrication resolution of handheld devices, and reprogrammers for photochromic material.

2.1 Color-Changing Systems in HCI

Researchers have explored color-changing systems with a variety of technologies and applications. Optical effects have been used to create dynamic patterns that interact passively with mechanical input. For example, *Polagon* [22] uses multi-layer birefringent material to show a variety of colors when the material is rotated. *Lenticular Objects* [28] uses lenticular lens structures to create objects that show different surface textures across multiple viewpoints. *MoiréWidgets* [3] uses the Moiré effect to create dynamic interference patterns through aligning of the layers with different offset values.

Color-changing materials are often used to create digitally controlled appearances on surfaces [8]. For example, electroluminescent materials are sprayed on object surfaces to turn them into single-color displays (*ProtoSpray* [10], *Object Skin* [7]). Upcycled e-ink films are used to create custom bi-stable black-and-white displays (*FabricatINK* [9]) with embedded electrodes turning them on and off. Active materials that interact with triggers other than electric field can also achieve controlled image change with specifically designed actuators. For example, thermochromic materials have been used in combination with various heating sources, such as embroidered conductive traces (*Embr* [5]) or fluid channels (*Thermotion* [27]), to create multi-state color patterns. Researchers have also created 3D-printed structures that react with magnets and use a robot hand to create reprogrammable patterns (*3D-Printed Magnetophoretic Displays* [26]). Closer to our work, *PhotoChromeleon* [12] and *PortaChrome* [29] use different light sources to control photochromic color-changing materials, whose color can be reprogrammed with light, achieving fully reprogrammable multicolor patterns.

2.2 Fabrication Resolution of Handheld Devices

HCI researchers have explored ways to combine the interactivity of a hand tool with the precision of a larger-scale digital fabrication machine. For instance, *FreeD* [30] presents a Dremel-like tool that only allows material removal in specific locations to achieve the precision of a CNC machine while providing an embodied experience. *D-Coil* [15] presents a handheld wax extruder with stabilized movement to achieve the precision close to a 3D printer. On 2D devices, *Rivers et. al* [18] develops a pattern-tracking system on a handheld 2D CNC, extending the scalability of CNC while keeping the product high-resolution. *Print-A-Sketch* [16] augments a handheld printer to allow for printing conductive ink on any surface while using a tracking system to achieve the precision required for electronic footprints. In the context of photochromic material interaction, *PortaChrome* [29] presents a portable version of *PhotoChromeleon* [12], its stationary counterpart, extending the color-change applications while sacrificing in resolution. In *ChromoLCD*, we introduce an approach to achieve such device portability while enabling a resolution comparable to its stationary counterpart.

2.3 Light Sources in Photochromic Reprogrammers

Researchers have used various light sources to achieve photochromic reprogrammers, including UV lasers, projectors, and LED matrices, to achieve different levels of color space, portability, and image resolution.

Laser-based reprogrammers use UV lasers to precisely saturate pixels on photochromic-coated surfaces, producing high-resolution images. For instance, *Slow Display* [20] uses an enclosed UV laser to draw vector images on photochromic paper. *UbiChromics* [2] uses a 405nm laser to create interactive traces room-scale surfaces. However, due to their vector-based nature, existing laser-based reprogrammers are limited to line-drawing styles and are only compatible with single-colored photochromic systems.

Projector-based reprogrammers archives high-resolution multicolor images by precisely aligning UV and RGB projectors to illuminate the same pixel with multiple wavelengths. This enables individual control over the cyan, magenta, and yellow photochromic channels, expanding the achievable color space of the photochromic system to close to that of traditional printers. Specifically, *Color-Mod* [17], *Photo-Chromeleon* [12] and *ChromoUpdate* [24] are stationary reprogrammers with a enclosed UV and RGB projectors and allow users to reprogram a photochromic object's surface texture by placing it on the the turn table and projecting from different angles. *ChromaNail* [6] miniaturizes this concept by embedding a projector and UV LED into a nail-curing machine, enabling multicolor patterns on photochromic nail polish during the curing process. *Photochromic Canvas* [11] embeds a small white-light projector into a brush-like handheld light source to create repeated single-color patterns on pre-saturated photochromic papers. Because projector-based reprogrammers require distance from the surface for projections, further miniaturization of projector-based programmers remains challenging.

LED-based reprogrammers, in contrast, come with great portability, extending the range of application of photochromic images. For instance, *Photochromic Carpet* [21] integrates UV LED matrices into user's shoes to create single-color binary patterns on carpets coated with photochromic dye as the user walks. *PortaChrome* [29] extends this interaction into multicolor by creating a hexagonal array of UV and RGB matrix and an optical diffuser to direct the light to the same pixels. However, the resolution of LED-based reprogrammers is limited by the size of the LEDs available, especially at UV wavelengths.

In *ChromoLCD*, we introduce a **liquid crystal display (LCD) panel** to achieve both the high resolution of projector-based reprogrammers and the portability of the LED-based ones. LCDs work by selectively blocking light at individual pixels, turning a uniform backlight into a high-resolution light pattern at its original wavelength. In addition, this approach inherently solves the challenges of aligning different wavelengths of light since all wavelengths pass through the same pixel matrix, allowing for multicolor photochromic images without complex optics.

3 CHROMO-LCD

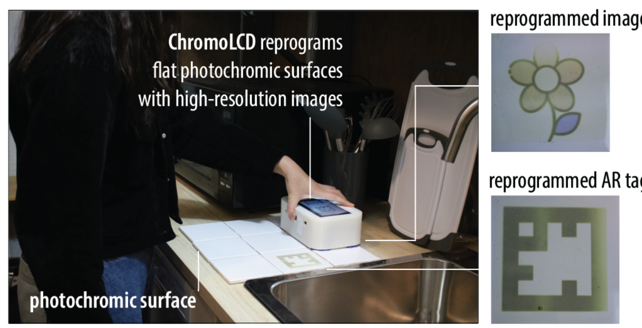

Figure 2: ChromoLCD is a high-resolution photochromic surface reprogrammer. To create a photochromic image, the user stamp the ChromoLCD device on surfaces previously coated with photochromic material.

3.1 ChromoLCD Interaction

ChromoLCD is a compact, high-resolution, and multicolor photochromic surface reprogrammer. To use it, the user holds ChromoLCD in direct contact with a surface that has been pre-coated with photochromic material. Figure 2 shows an example of on-the-fly reprogramming with ChromoLCD, where a user updates the patterns on kitchen tiles previously coated with photochromic dye. When in contact, ChromoLCD first illuminates the photochromic kitchen tiles with high-resolution light patterns at the wavelengths of UV (365nm) to saturate each pixel to its necessary saturation, activating cyan, magenta and yellow color channels at the same time. ChromoLCD then illuminates the photochromic surface with high-resolution light patterns at 444nm, 524nm and 656nm to individually desaturate each color channel to the required saturation level at each pixel. The resulting images are high resolution, and the compact form factor of ChromoLCD allows the user to reprogram any flat photochromic surface they can reach.

3.2 ChromoLCD Device

ChromoLCD consists of a monochromatic LCD panel paired with a custom backlight (Figure 3). This design allows high-resolution light patterns to be created in both UV and RGB wavelengths required to reprogram the multicolor photochromic material. Similar to the working principle of conventional LCD displays, the backlight creates uniform light while the monochromic LCD panel selectively controls whether the light from the backlight can pass through each pixel, allowing it to saturate or desaturate each pixel independently on the photochromic surface. Both the backlight and the LEDs are controlled by a microcontroller with a touch panel interface for user input and control. In the next paragraphs, we go through the design choices and fabrication details of all parts of ChromoLCD device, including the LCD panel, the backlight, and the control system.

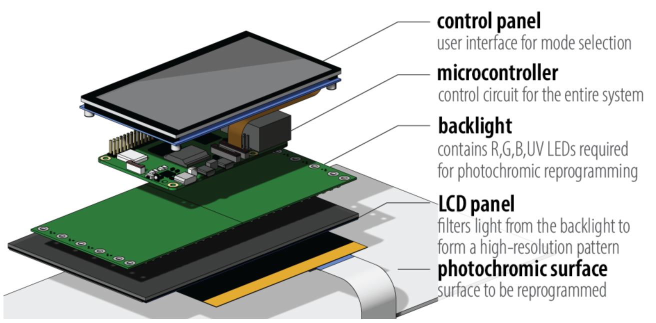

Figure 3: (ChromoLCD consists of an LCD panel that blocks light on a per-pixel basis and a backlight supplying both UV and RGB light of required wavelengths, allowing it to create reprogrammable high-resolution light patterns at the required wavelengths.

Table 1: LCD Panel Compatibility with 365nm UV Backlight

Screen Part #	Size	Color Type	Transmits at 365nm
LS055R1SX04	5.5 inch	RGB	No
DBT066MONO	6.6 inch	Monochromic	Yes
YG2011A0	6.6 inch	Monochromic	Yes
YM2305A0	10.1 inch	Monochromic	Yes
DBT101MONO	10.1 inch	Monochromic	Yes

LCD Panel: The LCD panel controls the shape of the light pattern that reaches the photochromic surface. In an LCD panel, each pixel can be electrically switched between a transmissive or opaque state. When a pixel is turned into its transmissive state, light from the backlight passes through the LCD to reach the photochromic surface while opaque pixels block the light.

Conventional RGB LCD displays create multicolor images by using a white backlight combined with red, green, and blue color filters for each pixel, filtering out unwanted wavelengths and thus allowing each pixel to display as red, green, or blue. This approach prevents UV light from passing through regardless of whether the pixel is turned on or off, as it is filtered out in all of the pixels. In contrast, monochromatic LCDs do not have filters. When a pixel is in its transmissive state, light of any wavelength can pass through. This allows us to achieve the wavelengths required for photochromic material by designing a custom backlight containing the wavelengths needed for saturation and desaturation.

Since many commercially available monochromatic LCDs contain UV filters [19], we source ours from LCD 3D printers, which are the primary application for UV-transmissive LCD panels. We test and evaluate the LCDs used in different models. Table 1 lists five LCD panels Since UV light transmissivity is not commonly tested as it is for visible wavelengths, we conducted our tests to find out whether they transmit UV light. Specifically, we displayed a stripe pattern using a 365nm UV backlight, which is required to saturate the photochromic material. After two minutes of exposure, we observed whether the pattern appeared on the photochromic surface in contact with the LCD (Figure 4a). The LCD panel in Elegoo Mars (part number: `LS055R1SX04`) turns out to be an RGB LCD, and thus allows no 365nm UV light to pass through, and is not suitable for ChromoLCD. Figure 4b shows the result and confirms that UV light does not pass through an RGB LCD panel. In contrast, the monochromatic LCD used in the Elegoo Mars 3 (part number: `YG2011A0`) successfully transmits 365nm UV light, forming the stripe pattern on the photochromic surface after exposure. This shows that it is suitable to be used in ChromoLCD (Figure 4c). Other monochromic panels form similar patterns. In this paper, we demonstrate our system using the LCD panel `YG2011A0` used in Elegoo Mars 3 because of its commercial availability as a 3D printer replacement part.

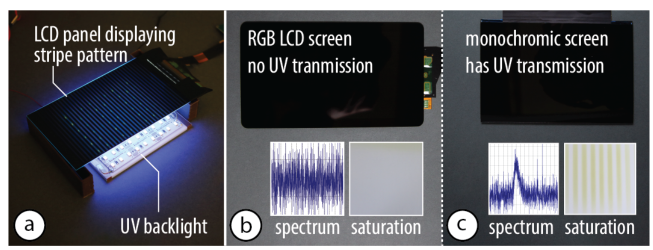

Figure 4: Comparison between LCD with different materials: (a) test whether an LCD panel is UV transmissive by displaying a stripe pattern with a UV backlight; (b) RGB LCD panels do not allow 365nm UV light to pass through; (c) monochromic LCD panels allow 365nm UV light to pass through.

Backlight: While the LCD panel controls the shape of the light pattern, the backlight provides the light itself, determining its wavelength and intensity. Since the photochromic material saturates under 365nm UV light and desaturates at individual color channels with different wavelengths of visible light [12], we select LEDs with wavelengths that optimize for individual control of the color channels. Specifically, we chose `WL-SUTW` as the UV LED, which has peak wavelength of 365nm and allows full saturation of all three color channels, and `L1SP-DRD0002800000`, `JE2835 GREEN` and L1SP-RYL0002800000, for the RGB LEDs with their measured wavelengths shown in Figure 5a.

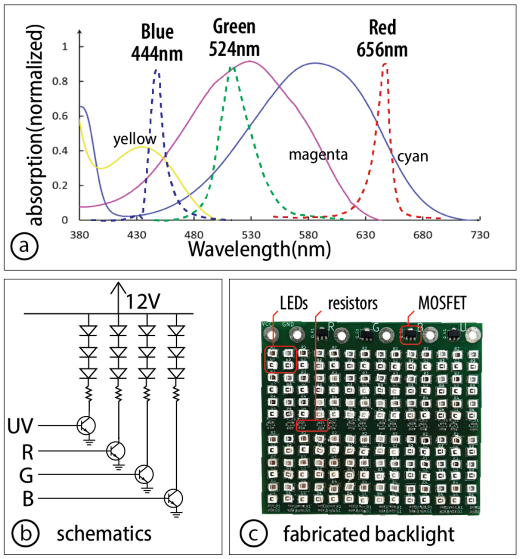

Figure 5: Backlight of ChromoLCD: (a) wavelengths of the LEDs on the backlight compared with the absorption spectrum of the photochromic color channels. (b) LEDs are connected in series of three and controlled by a MOSFET for each individual color; (c) manufactured PCB for the backlight.

The LEDs are powered by a 12V battery and in series of three, each color controlled through an N-channel MOSFET (Figure 5b). To optimize light intensity to achieve faster reprogramming, we packed the LEDs as closely together as possible (Figure 5c). In the resulting backlight, each color can be individually turned on or off with a 3.3V digital signal (Figure 5d).

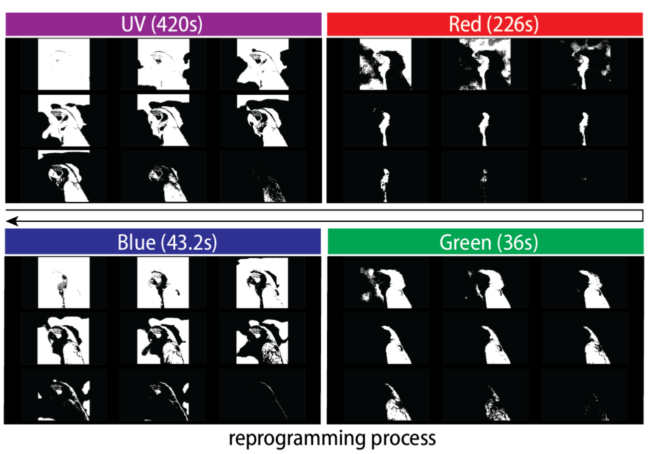

Figure 6: Image sequence on the LCD panel under each backlight color to form a multicolor pattern.

Control Circuit and Pattern Sequence: Both the LCD panel and the backlight are controlled with a Raspberry Pi 5 microcontroller powered by a power bank that has a 5V and a 12V output. The LCD panel is run by an HDMI driver board through the HDMI portal and powered by the 5V output. The backlight module is controlled via the GPIO pins on the microcontroller and powered by the 12V output.

The microcontroller computes the pattern sequence to be displayed on the LCD panel. To compute the desaturation time, we use the same algorithm as in ChromoUpdate [25]. Because of the limited processing speed of a microcontroller compared with the desktop computer used in prior work, we precomputed and stored all combinations of the required desaturation time to achieve a color to speed up the computation time (source code[1]).

Figure 6 shows the sequence of the light pattern displayed on the LCD panel to form the image in Figure 8b. Specifically, the backlight is turned on in the order of UV for saturation and R,G,B for desaturation, one at a time. Under each backlight color, the LCD panel displays a computed video that turns each pixel transmissive for a certain time to allow the backlight to pass through, achieving the desired saturation level for the color channels on that pixel.

4 USER INTERFACE

The ChromoLCD device is a standalone device and does not require connecting to an external computer to function. It has an integrated touchscreen interface on the device body. The user can select the image and the reprogramming mode to allow the device to show the light pattern that generates the specified image on the photochromic surface. We will demonstrate the texture-specifying process with the example of reprogramming a reference image on a photochromic-coated whiteboard.

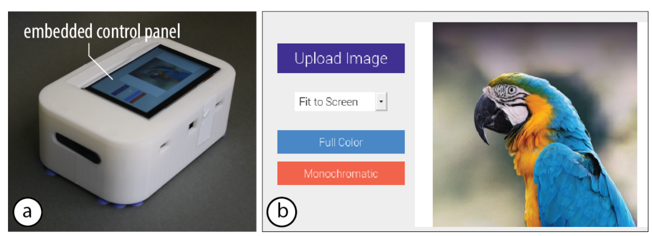

Figure 7: (a) The user interacts with ChromoLCD through a touchscreen interface. (b) The user selects the image to reprogram into.

Select Image: To select the target image to reprogram into, the user loads the image by selecting the "Select Image" button (Figure 7a). After the user specifies the image, the image will be displayed in the interface for the user to confirm (Figure 7b).

Color Reprogramming: The user selects the "Reprogram" button to start the reprogramming process. Because the color space of multicolor photochromics is smaller than that of the RGB color space due to the limitation of available photochromic dyes [12], the desaturated pattern will differ from the desired image. Therefore, when the user starts the process, a preview of the expected reprogrammed result and the time needed for the reprogramming will

[1]Source code will be released upon publication.

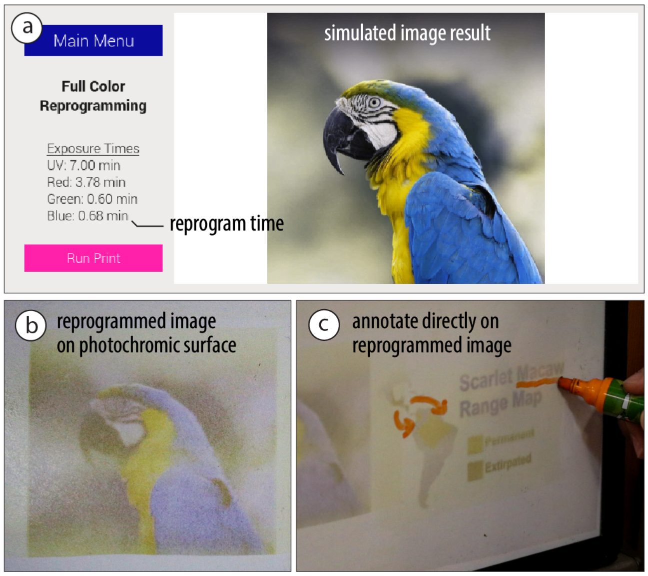

Figure 8: (a) Preview of the the reprogramming results; (b) reprogrammed physical result; (c) the user can interact with the physical result.

be displayed on the right (Figure 8a). After previewing the image, the user can select the "Start" button to start the image transfer process. Figure 8b shows the result of the reprogrammed image on the whiteboard, which took 11 minutes. The user can annotate on top of the reprogrammed image with a whiteboard marker (Figure 8c).

5 EVALUATION

In this section, we evaluate the performance of ChromoLCD by measuring its achievable resolution and the saturation and desaturation curves of the color channels. We also characterize the monochromatic LCD panel by measuring its transmittance and contrast ratio on the color channels.

5.1 Resolution

Apparatus and Procedure: While the ChromoLCD has a 4k resolution LCD panel, other factors, such as the diffusion when light travels through the front glass panel covering the liquid crystal and the surface diffusion on the photochromic surface, can yield a different resolution of the resulting photochromic pattern. We measure the resolution of ChromoLCD by creating a pattern with square pixels of side lengths ranging from 1mm to 20mm, reprogramming photochromic surfaces of different textures with this pattern, and observing the result.

Results: Figure 9 shows the resulting resolution of the pixels with different side lengths. The vinyl device casing, which has a textured surface, has identifiable pixels of 2mm width. In comparison, the clay panel, which has a smooth surface, has identifiable pixels of 1mm width. This is likely because smooth surfaces are in better contact with the LCD panel and thus have less surface diffusion.

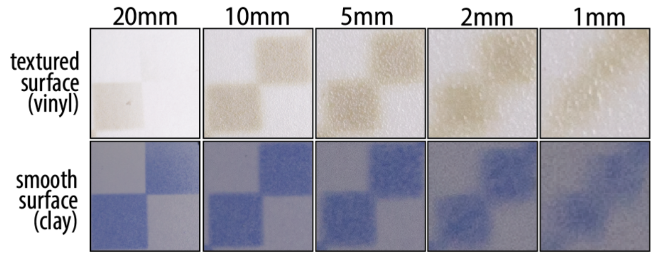

Figure 9: The pixel resolution on photochromic surfaces of surface textures.

5.2 Transmittance of LCD Display

Apparatus and Procedure: The transmittance of an LCD measures the percentage of light that can pass through the display [13]. When LCD panels are turned on, pixels on the LCD can be turned into a state that shows high transmittance, allowing the backlight to pass through. In the context of ChromoLCD, the transmittance of the LCD determines the efficiency of the device. To measure the transmittance of the ChromoLCD display, we used a spectrometer (model: Thorlab CSS200) to measure the spectrum and equivalent light intensity at the same location with no LCD panel, an LCD panel at its transmissive state (turned on) and one at its opaque state (turned off). During the measurement, the probe is secured at the same location, and the light integration time is kept consistent for each color.

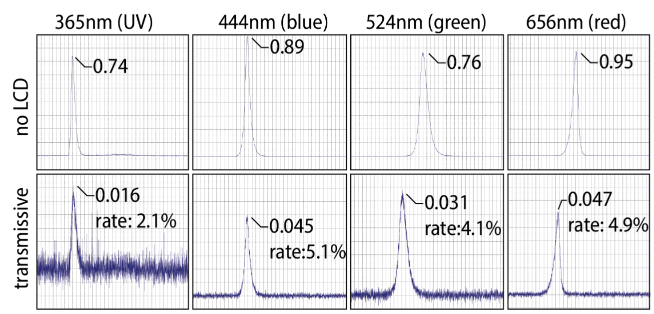

Figure 10: Transmittance of LCD panel in ChromoLCD: 2.1% under wavelength of 365nm, 5.1% under 444nm, 4.1% under 524nm and 4.9% under 656nm. Plots are scaled for better readability.

Result: Figure 10 shows the transmittance of the LCD panel in ChromoLCD under the four wavelengths supported by the backlight. The measurement of the UV light is scaled for ease of observation. The measured transmittance of the LCD panel in the ChromoLCD is 2.1% for UV light at 365nm, 5.1% for blue light at 444nm, 4.1% for green light at 524nm and 4.9% for red light at 656nm. This is consistent with the transmittance of the conventional LCD, which is 4% to 7% [1]. Because of the scarcity of UV applications, commercially available LCD panels are not optimized for UV backlight, resulting in lower transmittance than other bands.

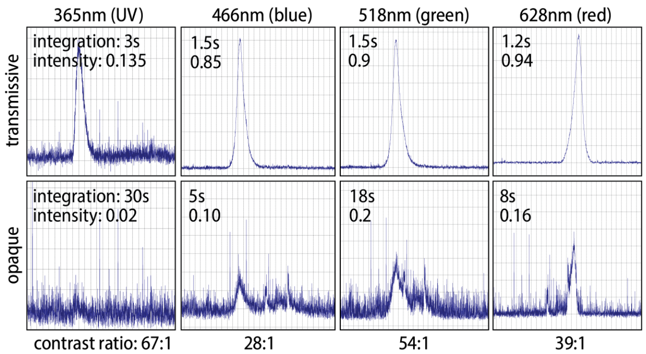

Figure 11: Contrast ratio of the LCD panel of ChromoLCD: 67:1 under 365nm, 28:1 under 466nm, 54:1 under 518nm and 39:1 under 628nm.

5.3 Contrast Ratio of ChromoLCD

Apparatus and Procedure: The contrast ratio determines the contrast in light intensity between a transmissive pixel and an opaque pixel. It is calculated by dividing the light intensity at the transmissive state with the light intensity at the opaque state of the screen. Because of the noise from the environment and the limited range of light intensity detectable, we measure the spectrum and the equivalent light intensity at a higher integration rate to get a more accurate reading when the screen is at its opaque state. We then compute the contrast ratio with equivalent light intensities calculated by dividing the light intensity with the integration time.

Result: Figure 11 shows that the LCD panel of ChromoLCD has a contrast ratio of 67:1 under 365nm, 28:1 under 466nm, 54:1 under 518nm and 39:1 under 628nm. Assuming linear saturation and desaturation, this introduces slight noise to the pattern created. In Section 7, we discuss how to algorithmically address the imperfect contrast ratio of the LCD panel.

5.4 Saturation and Desaturation Time

Apparatus: To evaluate the color reprogramming time, we measured the time for saturation and desaturation on white ceramic blocks sprayed with photochromic dye of a single color channel. We used the same method as in *ChromoUpdate* [25], where we made sprayable photochromic material by mixing photochromic material with Dupli-Color EBSP30000 Glossy Clear Coat spray paint at a concentration of 0.033w% cyan, 0.033w%magenta, and 0.1w% yellow, respectively.

Procedure: For saturation, we illuminate a gradient of UV light for 10 minutes for cyan, 10 minutes for magenta and 1 minutes for yellow, allowing them to achieve full saturation. For desaturation, we first fully saturate each panel under UV light and illuminate a gradient on all samples for 10 minutes for red light, and 1 minute for green and blue light.

Result: Figure 12 and Figure 13 show the resulting color gradient achieved by illuminating the described color pattern. We find the number of minutes when each dye is desaturated to 5%, and use it as

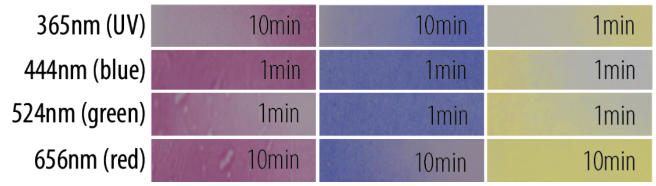

Figure 12: Saturation and desaturation across each color channel at each wavelength.

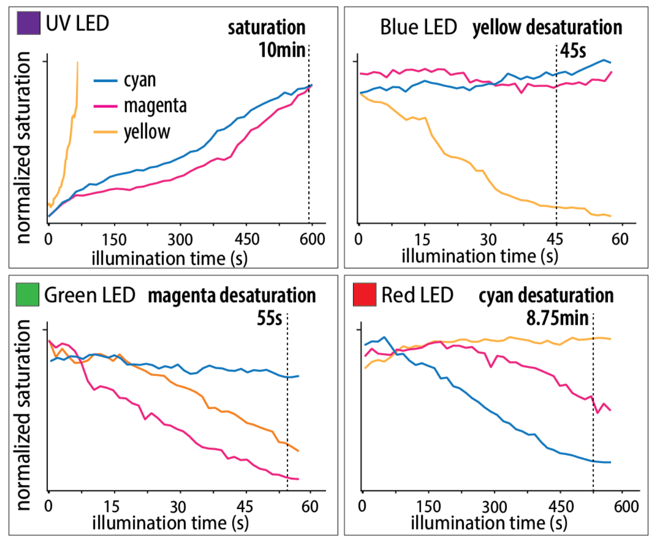

Figure 13: Normalized saturation and desaturation process across each color channel at each wavelength.

the full saturation time used in the desaturation algorithm for linear combination. The resulting saturation time for the color channels under UV light is 10, 10 and 1 minute, while the desaturation time is 45 seconds, 55 seconds and 8.75 minute using their primary desaturation wavelength.

6 APPLICATION

Due to its handheld form factor, ChromoLCD allows for making high-resolution photochromic images in the user's physical surroundings. In this section, we demonstrate how users can benefit from this reprogramming interaction with three applications: on-the-fly design changes on the user's accessories, reprogrammable AR markers in the user's physical surroundings, and reference images on an interactive whiteboard.

6.1 On-the-fly Reprogramming of Personal Garment Design

The portability of ChromoLCD allows it to be taken on the go and reprogram surfaces independent of the user's physical location. Figure 14 demonstrates this potential with the example of reprogramming the designs of a bag for different occasions while the user is outside. The user reprograms it with a professional stripe design at work and when they step out from work, they can change

Figure 14: (a) ChromoLCD can be used to reprogram the user's accessory with various high-resolution designs on-the-fly. (b) A graffiti design for casual occasions, a geometric design for professional occasions, and a floral design for travel and relaxation.

it to a playful design (Figure 14b). In this application, the designs took 8, 9, 8 minutes to reprogram, respectively.

6.2 Reprogrammable AR Markers in the Physical Surrounding

Compared with previous desktop-scale systems, ChromoLCD is more compact, allowing users to use it like a stamp and create high-resolution images in their physical surroundings. Figure 15 demonstrates this potential with the example of stamping AR markers on the kitchen counter. Figure 15b shows the two AR tags that display recipe reference and cooking tutorial, and a flower image that displays home decor in the AR space. Figure 15c shows how an environment like this can look in AR to facilitate cooking. In this application, both AR tags took 7 minutes to reprogram, and the flower took 15 minutes.

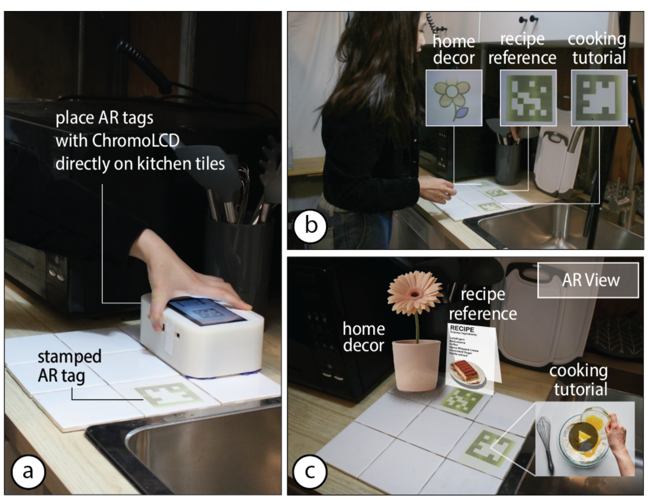

Figure 15: The portability of ChromoLCD allows it to be used to create AR markers on the user's physical surroundings, such as on the kitchen counter to show a recipe reference and cooking tutorial.

6.3 Reference Images for Interactive Teaching

One of the advantages of the photochromic material is its ability augment physical surroundings with digital capabilities while preserving their original form and functionality. Figure 16 illustrates how ChromoLCD can maximize this potential with an example of interactive teaching on a photochromic-coated whiteboard. In the example, the user can stamp on multicolor reference diagrams and images with ChromoLCD (Figure 16), such as the picture of a Macaw parrot and the map of their habitat (Figure 16b). The user can then annotate it on the physical whiteboard with the reference image just like a normal whiteboard (Figure 16c). In this application, the whiteboard the parrot took 11 minutes to reprogram and the diagram took 20 minutes.

7 LIMITATION AND FUTURE WORK

We next discuss the limitations of our approach and avenues for future work.

Adapting Existing LCD Technologies: While ChromoLCD currently uses a 6.6-inch LCD panel sourced from 3D printers to create a handheld photochromic reprogrammer, many existing LCD production lines could be adapted for photochromic requirements at the manufacturing level. The primary barrier are the RGB color filters and UV protection filters, which block the UV wavelengths needed for photochromic saturation. By omitting these filters during manufacturing or including empty pixels, many LCD form factors become viable for photochromic reprogramming. For example, large LCD panels such as those in televisions could be controlled by robotic systems and tiled to create wall arts. Similarly, small LCDs from smartwatches could be worn as personal accessories to stamp signatures or custom patterns.

Interactive Reprogramming: ChromoLCD allows objects to have on-the-fly dynamic appearance while preserving their physical texture and feel, it currently only supports stamping interactions. In future work, we plan to combine an optical mouse sensor with an AprilTag-based camera tracking system to allow users to swipe scalable images onto large surfaces.

Curved Surfaces: While ChromoLCD achieves both high-resolution light patterns and compact form factor, it only reprograms surfaces that are flat or can be made flat. This is because commercially available LCDs commonly involve flat glass substrates to keep the

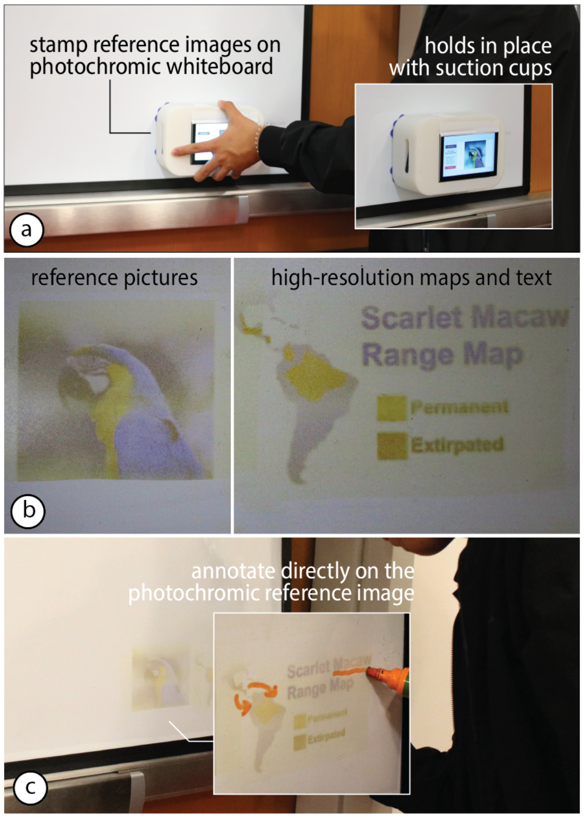

Figure 16: (a) ChromoLCD can be used to stamp reference images and diagrams on a photochromic whiteboard. (b) Physical result after reprogramming. (c) The user can then annotate on the physical whiteboard with a conventional whiteboard marker.

precise distance of the liquid crystal matrices. However, because of the abundance of flat and conformable surfaces in the physical surrounding such as walls and clothing, ChromoLCD still covers a significant application space even with the current limitation. In the future, researchers can explore the use of other types of LC displays, such as flexible PDLC displays that are proved to make flexible transmissive displays [4].

LCD Transmittance of UV Light: Because of the lack of commercial application of 365nm UV Light, the transmittance of the screens that we have on UV is 2.1%. While this allows for the UV to pass through and generate patterns, it is lower than that of visible light and results in a longer saturation time and lower energy efficiency. Resolving this requires the development of liquid crystal with a bandwidth that optimizes for the transmittance of 365nm UV light, such as with the use of wire grid polarizers [19].

8 CONCLUSION

In this paper, we introduced ChromoLCD, the first LCD-based reprogrammer for multicolor photochromic surfaces. ChromoLCD combines the portability of an LED-based reprogrammer and the high resolution of a projector-based one. Combining an LCD panel with a backlight with LEDs of the required wavelengths, ChromoLCD achieves high-resolution light patterns at the required wavelengths. ChromoLCD opens up new applications of photochromic materials, such as creating reprogrammable AR markers in physical spaces, altering the designs of personal accessories, and including reference images on a physical whiteboard. While the current implementation of ChromoLCD has limited flexibility, this compact reprogrammer for photochromic material based on digitally-controlled occlusion has the potential to broaden the interaction of photochromic reprogramming significantly and achieve a set of rich interactions, such as rolling and swiping.

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REFERENCES

[1] 2023. Optical efficiency modulation of vertical alignment liquid crystal displays with transparent shielding and storage electrode. *Displays* 77 (2023), 102407. https://doi.org/10.1016/j.displa.2023.102407

[2] Amani Alkayyali, Yasha Iravantchi, Jaylin Herskovitz, and Alanson P. Sample. 2022. UbiChromics: Enabling Ubiquitously Deployable Interactive Displays with Photochromic Paint. 6, ISS, Article 561 (2022). https://doi.org/10.1145/3567714

[3] Daniel Campos Zamora, Mustafa Doga Dogan, Alexa F Siu, Eunyee Koh, and Chang Xiao. 2024. MoiréWidgets: High-Precision, Passive Tangible Interfaces via Moiré Effect. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 329, 10 pages. https://doi.org/10.1145/3613904.3642734

[4] Christine Dierk, TJ Rhodes, and Gavin Miller. 2022. Project Primrose: Reflective Light-Diffuser Modules for Non-Emissive Flexible Display Systems. *ACM Symposium on User Interface Software and Technology* (2022). https://doi.org/10.1145/3526113.3545625

[5] Shreyosi Endow, M. Rakib, Anvay Srivastava, Sara Rastegarpouyani, and Cesar Torres. 2022. Embr: A Creative Framework for Hand Embroidered Liquid Crystal Textile Displays. *CHI* (2022). https://doi.org/10.1145/3491102.3502117

[6] Magnus Frisk, Mads Vejrup, Frederik Kjaer Soerensen, and Michael Wessely. 2023. ChromaNails: Re-Programmable Multi-Colored High-Resolution On-Body Interfaces using Photochromic Nail Polish. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 72. https://doi.org/10.1145/3586182.3615824

[7] Daniel Groeger and Jürgen Steimle. 2018. ObjectSkin: Augmenting Everyday Objects with Hydroprinted Touch Sensors and Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* (2018). https://doi.org/10.1145/3161165

[8] Ollie Hanton, Mike Fraser, and Anne Roudaut. 2024. DisplayFab: The State of the Art and a Roadmap in the Personal Fabrication of Free-Form Displays Using Active Materials and Additive Manufacturing.. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 333. https://doi.org/10.1145/3613904.3642708

[9] Ollie Hanton, Zichao Shen, Mike Fraser, and A. Roudaut. 2022. FabricatINK: Personal Fabrication of Bespoke Displays Using Electronic Ink from Upcycled E Readers. *International Conference on Human Factors in Computing Systems* (2022). https://doi.org/10.1145/3491102.3501844

[10] Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and A. Roudaut. 2020. ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes. *CHI Extended Abstracts* (2020). https://doi.org/10.1145/3334480.3383174

[11] Tomoko Hashida, Yasuaki Kakehi, and Takeshi Naemura. 2010. Photochromic Canvas Drawing with Patterned Light. In *ACM SIGGRAPH 2010 Posters (SIGGRAPH '10)*. Association for Computing Machinery, Article 26. https://doi.org/10.1145/1836845.1836873

[12] Yuhua Jin, Isabel Qamar, Michael Wessely, Aradhana Adhikari, Katarina Bulovic, Parinya Punpongsanon, and Stefanie Mueller. 2019. Photo-Chromeleon: Re-Programmable Multi-Color Textures Using Photochromic Dyes. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*

(UIST '19). Association for Computing Machinery, 701–712. https://doi.org/10.1145/3332165.3347905

[13] James J. Licari and Dale W. Swanson. 2011. Chapter 7 - Test and Inspection Methods. In *Adhesives Technology for Electronic Applications (Second Edition)* (second edition ed.), James J. Licari and Dale W. Swanson (Eds.). William Andrew Publishing, Oxford, 345–377. https://doi.org/10.1016/B978-1-4377-7889-2.10007-5

[14] Chien-Chung Lin, Yuh-Renn Wu, Hao-Chung Kuo, Matthew S Wong, Steven P DenBaars, Shuji Nakamura, Ayush Pandey, Zetian Mi, Pengfei Tian, Kazuhiro Ohkawa, Daisuke Iida, Tao Wang, Yuefei Cai, Jie Bai, Zhiyong Yang, Yizhou Qian, Shin-Tson Wu, Jung Han, Chen Chen, Zhaojun Liu, Byung-Ryool Hyun, Jae-Hyun Kim, Bongkyun Jang, Hyeon-Don Kim, Hak-Joo Lee, Ying-Tsang Liu, Yu-Hung Lai, Yun-Li Li, Wanqing Meng, Haoliang Shen, Bin Liu, Xinran Wang, Kai-ling Liang, Cheng-Jhih Luo, and Yen-Hsiang Fang. 2023. The micro-LED roadmap: status quo and prospects. *Journal of Physics: Photonics* 5, 4 (2023). https://doi.org/10.1088/2515-7647/acf972

[15] Huaishu Peng, Amit Zoran, and François Guimbretière. 2015. D-Coil: A Hands-on Approach to Digital 3D Models Design. *CHI* (2015). https://doi.org/10.1145/2702123.2702381

[16] Narjes Pourjafarian, Marion Koelle, Fjolla Mjaku, P. Strohmeier, and Jürgen Steimle. 2022. Print-A-Sketch: A Handheld Printer for Physical Sketching of Circuits and Sensors on Everyday Surfaces. *CHI* (2022). https://doi.org/10.1145/3491102.3502074

[17] Parinya Punpongsanon, Xin Wen, David S. Kim, and Stefanie Mueller. 2018. *ColorMod: Recoloring 3D Printed Objects Using Photochromic Inks*. Association for Computing Machinery, 1–12. https://doi.org/10.1145/3173574.3173787

[18] Alec R. Rivers, Ilan E. Moyer, and F. Durand. 2012. Position-correcting tools for 2D digital fabrication. *ACM Trans. Graph.* (2012). https://doi.org/10.1145/2185520.2185584

[19] Nicholas A. Rodriguez, Hongtao Song, Morgan Chen, James S. Oakdale, Eric B. Duoss, Carolyn C. Seepersad, and Richard H. Crawford. 2022. Use of wire grid polarizers with liquid crystal display for large-volume stereolithography. *Additive Manufacturing* 52 (2022), 102641. https://doi.org/10.1016/j.addma.2022.102641

[20] Daniel Saakes, Kevin Chiu, Tyler Hutchison, Biyeun M. Buczyk, Naoya Koizumi, Masahiko Inami, and Ramesh Raskar. 2010. Slow Display. In *ACM SIGGRAPH 2010 Emerging Technologies (SIGGRAPH '10)*. Association for Computing Machinery, Article 22, 1 pages. https://doi.org/10.1145/1836821.1836843

[21] Daniel Saakes, Takahiro Tsujii, Kohei Nishimura, Tomoko Hashida, and Takeshi Naemura. 2013. Photochromic Carpet: Playful Floor Canvas with Color-Changing Footprints. In *Advances in Computer Entertainment*, Dennis Reidsma, Haruhiro Katayose, and Anton Nijholt (Eds.). Springer International Publishing, 622–625.

[22] Ticha Sethapakdi, Laura Huang, Vivian Hsinyueh Chan, Lung-Pan Cheng, Fernando Fuzinatto Dall'Agnol, Mackenzie Leake, and Stefanie Mueller. 2023. Polagons: Designing and Fabricating Polarized Light Mosaics with User-Defined Color-Changing Behaviors. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 268. https://doi.org/10.1145/3544548.3580639

[23] Ticha Sethapakdi, Paris Myers, Tianyu Yu, Juliana Covarrubias, Mackenzie Leake, and Stefanie Mueller. 2024. Thermochromorph: Dynamic Relief Printing with Thermochromic Inks. In *SIGGRAPH Asia 2024 Art Papers*. Association for Computing Machinery, New York, NY, USA, Article 11. https://doi.org/10.1145/3680530.3695445

[24] Michael Wessely, Yuhua Jin, Cattalyya Nuengsigkapian, Aleksei Kashapov, Isabel P. S. Qamar, Dzmitry Tsetserukou, and Stefanie Mueller. 2021. ChromoUpdate: Fast Design Iteration of Photochromic Color Textures Using Grayscale Previews and Local Color Updates. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, Article 666. https://doi.org/10.1145/3411764.3445391

[25] Michael Wessely, Yuhua Jin, Cattalyya Nuengsigkapian, Aleksei Kashapov, Isabel P. S. Qamar, D. Tsetserukou, and Stefanie Müller. 2021. ChromoUpdate: Fast Design Iteration of Photochromic Color Textures Using Grayscale Previews and Local Color Updates. *CHI* (2021). https://doi.org/10.1145/3411764.3445391

[26] Zeyu Yan, Hsuanling Lee, Liang He, and Huaishu Peng. 2023. 3D Printing Magnetophoretic Displays. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 54. https://doi.org/10.1145/3586183.3606804

[27] Tianyu Yu, Weiye Xu, Haiqing Xu, Guanhong Liu, Chang Liu, Guanyun Wang, and Haipeng Mi. 2023. Thermotion: Design and Fabrication of Thermofluidic Composites for Animation Effects on Object Surfaces. *International Conference on Human Factors in Computing Systems* (2023). https://doi.org/10.1145/3544548.3580743

[28] Jiani Zeng, Honghao Deng, Yunyi Zhu, Michael Wessely, Axel Kilian, and Stefanie Mueller. 2021. Lenticular Objects: 3D Printed Objects with Lenticular Lens Surfaces That Can Change their Appearance Depending on the Viewpoint. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1184–1196. https://doi.org/10.1145/3472749.3474815

[29] Yunyi Zhu, Cedric Honnet, Yixiao Kang, Junyi Zhu, Angelina Zheng, Kyle Heinz, Grace Tang, Luca Musk, Michael Wessely, and Stefanie Mueller. 2024. PortaChrome: A Portable Contact Light Source for Integrated Re-Programmable Multi-Color Textures. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery.

[30] Amit Zoran and J. Paradiso. 2013. FreeD: a freehand digital sculpting tool. *CHI* (2013). https://doi.org/10.1145/2470654.2481361