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Research Article

TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays

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TransPrint is a method for fabricating flexible, transparent free-form displays based on electrochromism. Using screen-printing or inkjet printing of electrochromic ink, plus a straightforward assembly process, TransPrint enables rapid prototyping of displays by nonexperts. The displays are nonlight-emissive and only require power to switch state and support the integration of capacitive touch sensing for interactivity. We present instructions and best practices on how to design and assemble the displays and discuss the benefits and shortcomings of the TransPrint approach. To demonstrate the broad applicability of the approach, we present six application prototypes.

1. Introduction

Decreasing price and the widespread adoption of mobile and wearable devices have driven a dramatic increase in the amount of digital displays we encounter in our everyday lives. However, our environment still contains far more nondigital printed graphics, such as labels, signs, posters, and books, than digital displays. Static text and graphics printed on paper and other objects have been one of our major information sources for many years and will continue to be so. While, in many applications, digital displays aim to emulate the properties of printed graphics, they are limited to a rigid flat rectangular form factor. This limitation restricts the possibilities to seamlessly integrate such displays into our surroundings.

Recently, the field of printed electronics has developed to the point at which thin and deformable interactive prototypes can be created at low cost, e.g., as design prototypes [1–3]. Prior work has focused on extending printing methods to create interactive materials such as flexible touch sensors, thin film displays, and even haptic feedback [4–7]. Especially, printed electronics displays have the potential to overcome the limitations of current digital display technologies, enabling more interactivity and new form-factors. Moving away from the square pixel-based architecture, which is dominant in today's display technologies, has been highlighted as a key factor to deliver truly ubiquitous technologies [8].

In this paper, we present TransPrint, an adaptable method that enables the production of flexible, transparent displays in highly customizable shapes by the maker community and other nonexperts (see Figure 1). TransPrint is based on electrochromism (EC), i.e., the property of materials to reversibly switch their optical properties, e.g., colour, through electrochemical oxidization. For TransPrint, this switch is between near-transparency and a dark blue opaque colour.

One of the key traits of displays based on electrochromic systems is that they are nonlight-emissive. This distinguishes them from LED and electroluminescence (EL) based displays [4, 6]. Given the negative impact of artificial light on human sleep patterns [9], this property is particularly beneficial for ubiquitous always-on displays, e.g., as part of Internet of Things (IoT) solutions. Together, the properties of TransPrint displays enable smart solutions that are embedded to the existing objects and surfaces of our environment, fulfilling

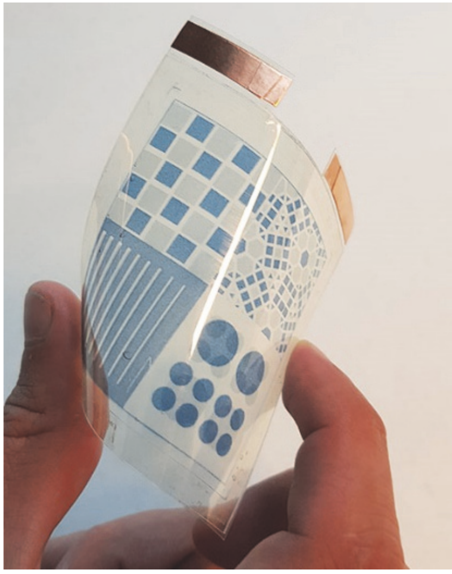

Figure 1: A display created with TransPrint.

Mark Weiser's vision of technologies that "weave themselves into the fabric of everyday life" [10].

While EC-based displays have been well established and most characteristics of the different materials have been well investigated in the past, constructing these displays usually required laboratory settings [11]. With TransPrint we present a method that allows nonexperts to produce EC-based displays with commercially available materials. We present two ways of printing such displays using either screen-printing or inkjet printing. Both methods are rapid and inexpensive and only require a limited amount of hardware and technical knowledge. We show how to integrate these printed displays with static printed elements as well as new application scenarios stemming from the unique traits of TransPrint displays. Furthermore, we discuss how support for capacitive touch input can be easily incorporated. With this we hope to enable the community to adapt such displays and embed them in future research, e.g., in the realm of printed electronics for interaction.

In this paper, we firstly discuss related work in the fields of printed electronics and displays, focusing on electrochromic systems and transparent displays. We then provide background on the operation of electrochromic displays in general and describe the TransPrint approach to design, print, and assemble displays. Following this, we present an analysis of the key characteristics of the created displays. Finally, we present a set of application cases that demonstrate the possibilities of TransPrint displays.

2. Related Work

2.1. Printed Electronics Prototyping. Recently, an increasing amount of research has focused on using printed electronics in Human Computer Interaction (HCI) and UbiComp applications. Printed electronics allow the fabrication of thin and deformable electronic systems that can cover large areas and be integrated with other materials, thus challenging our traditional view of electronic circuits as flat and rigid [3], to the level of printed circuits for temporary rub-on tattoos [12]. Initial work conducted by Gong et al. leveraged inkjet printed conductive materials for a wide variety of sensing applications [13]. Savage et al. introduced the Midas platform enabling the fabrication of custom touch sensing circuits utilizing vinyl cutting [14]. Following on from this, Kawahara et al. proposed a method to print circuit patterns designed using standard inkjet printers and software [2]. This method has been adopted to create a wide variety of different applications such as, e.g., customizable touch sensors [15, 16], which can be cuttable [5], epidermal pressure sensors [17], deformation sensors [18], and even energy harvesting devices [19]. Recently Kato et al. used double-sided conductive ink printing to fabricate paper gloves that deliver electrical stimulus to create a pseudo-tactile sensation [20]. Olberding et al. combined many of these fabrication and sensing mechanisms with actuation capabilities into their Foldio approach [21], which Wessely et al. recently extended, to reusable origami style elements [22]. Furthermore, there are even self-actuated paper prototypes that can be printed using conductive PLA [23].

A variety of different approaches to print these new materials have been presented, the most common being inkjet printing and screen-printing. Recently hydroprinting—printing via water transfer—has been employed to print touch screens on highly curved organic geometries [24]. Kuznetsov et al. analysed the potential of screen-printing as a DIY fabrication technique for embedding interactive behaviour onto a range of substrates [25]. They conducted workshops in Science, Technology, Engineering, Arts, and Mathematics (STEAM) contexts and found that it has a relatively low barrier to entry for smart material fabrication and supports collaboration and creative engagement.

Building on these previous approaches, TransPrint employs inkjet and screen-printing in the creation of our displays and aims to enable the combination of printed EC displays with other printed electronics prototyping techniques, hence, enabling easy integration into wider printed electronics prototyping pipeline.

2.2. Thin Film Displays. A major distinction when it comes to thin film display technologies is whether the display is pixel-addressable such as OLED and E-Ink, or a graphical segment-based display in which only predefined shapes can be switched. Although the second category offers less visual dynamicity, it provides advantage in other areas, such as ease of fabrication and possibility of creating displays in a variety of shapes and forms. Common technologies to realize thin film displays are, e.g., ultraviolet [26], thermochromism [27, 28], electroluminescence (EL) [4, 6, 29], and electrochromism (EC) [4, 30, 31], each having relative advantages and disadvantages. Ultraviolet-based displays require an additional light source and can suffer from low visibility in daylight conditions. Thermochromism is hard to control, due to the need for exact temperature control and the potential influence of ambient temperature. EC and EL displays are easy to fabricate at low cost and are flexible, robust, and

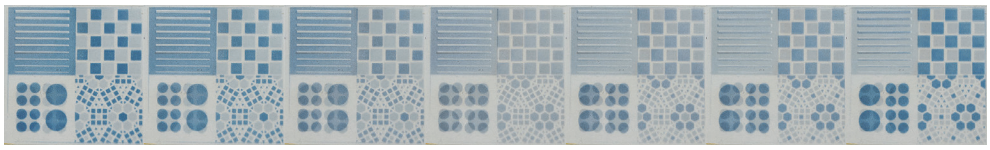

Figure 2: A displays switch from one state to the other. Left side shows one side fully switched, middle balanced state and right the opposite fully switched.

low-power consuming. EL displays have a relatively long lifetime of up to 50,000 hours and, in comparison to EC, have faster switching times [6], making EL suitable for lighting applications [6, 32]. (Switching time here refers to the time it takes to switch from on state, e.g., an off state where nothing is shown to another state where something else is shown.) Different techniques have been proposed for the production of EL displays, such as cutting segments from a larger EC film [33], and screen- and inkjet printing the substrate layers [6]. Olberding et al. demonstrated the possibilities of such displays with a design space that included different materials as well as a variety of application cases [6]. Additionally, screen-printed EL displays can be integrated with textiles [34]. Klamka and Dachselt extended the EL design space with their exploration into the possibilities of added pen interaction [4]. EC-based displays have several promising properties; for example, they can hold their display content for an amount of time without a battery, like e-ink displays. As with e-ink displays, they do not emit any light themselves and they have a comparably slow switching time between states. Previous work on EC displays investigated the capabilities for mass-manufacturing [35], manual manufacturing processes [30], and even developed multilayered colour displays [31]. One of the main application cases for electrochromism so far is smart windows [36–38], while, more recently, other HCI applications have been explored. Klamka and Dachselt used an EC-based 8-segment display in their IllumiPaper prototype and Vyas et al. used an EC-based display that changed opacity with the increasing dust level of a vacuum cleaner [4, 39]. With TransPrint, we extend this line of work by presenting a fabrication process that enables nonexperts to produce such displays and demonstrating the capabilities of EC-based displays for a wider range of mobile and wearable UbiComp and HCI prototypes. Compared to previous work, we specifically provide detailed instruction on the design, printing, and assembly processes for transparent EC displays, which are based on commercially available materials and can be fabricated in nonlaboratory settings with simple prototyping equipment.

3. Electrochromic Displays

Electrochromism is the capability of some materials to reversibly change colour stimulated by redox reactions. This means that EC materials can change their optical absorption characteristics or colour when an electrical voltage is applied. A variety of different materials exist that can switch between different colour combinations and intensities. For TransPrint we are using the PEDOT:PSS (the chemical name poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) mixture for printing, which can change its colour from nearly transparent to a darker blue. The PEDOT:PSS mixture exhibits EC properties because it is electrochemically active which makes it suitable as electrodes in EC displays and operates at low voltages (1-5 volt). Additionally it takes few seconds (< 3s) and requires low current draws (< 3mA) to switch a 5x5cm display fabricated with PEDOT:PSS. However, one thing to note is switch time and current draw heavily depends on size and graphics design (amount of PEDOT:PSS used).

EC displays have several characteristic properties that enable a variety of applications [11]. They exhibit open circuit memory where its state stays the same when there is no short circuit, similar to electrical batteries, and can maintain their optical state and electrical charge for extended periods of time while drawing comparably little energy. This means that once the display reaches the desired visual state, no further energy is required to maintain the state. Energy is only needed to create a state change. The optical absorption (or in practice the strength of colouration) can be calibrated and set to any level between the states of minimum and maximum absorption; see Figure 2. Compared to EL displays, the optical state transitions of EC displays are slow, typically lasting a few seconds, depending on physical dimensions and used materials. While some EC materials can take tens of minutes to switch, the PEDOT:PSS employed for TransPrint switches in less than 10 seconds even at A4 size prints. EC displays do not emit any light; they only change the amount of light they absorb. Given that the increasing amount of artificial light in our daily life—especially from digital displays—has been shown to lead to disrupted sleep patterns and increased sleep deficiency [9], the nonlight-emissivity of EC displays presents an opportunity for more ubiquitous display deployment.

To date, EC technology has predominantly been used in windows and smart glass, enabling dynamic change of optical and thermal characteristics [36–38]. This is because the change of the absorption happens on an atomic level and therefore allows EC windows to switch without visible haze [40]. Recent advances have shown EC to be usable as an anticounterfeiting method by applying electrochromic materials to paper [41]. While EC is a rather old and well-established technology in the field of organic chemistry, it has so far mostly been neglected for HCI research [4, 38, 39]. One possible factor for this is the problem of fabricating such displays, which we try to overcome with the TransPrint method.

A functioning EC display is composed of the following components: two conductors (electrodes) each connected to a field of EC material or 'ink', and electrolyte which separates the two fields of EC material (see Figure 3). The conductors create an electrical circuit by allowing electrons and ions to

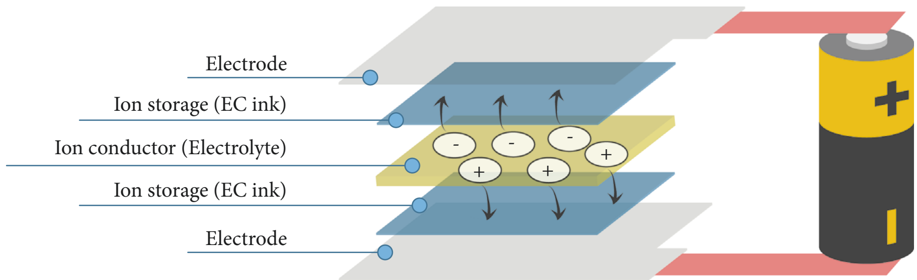

FIGURE 3: Composition of vertical stacked electrochromic technology.

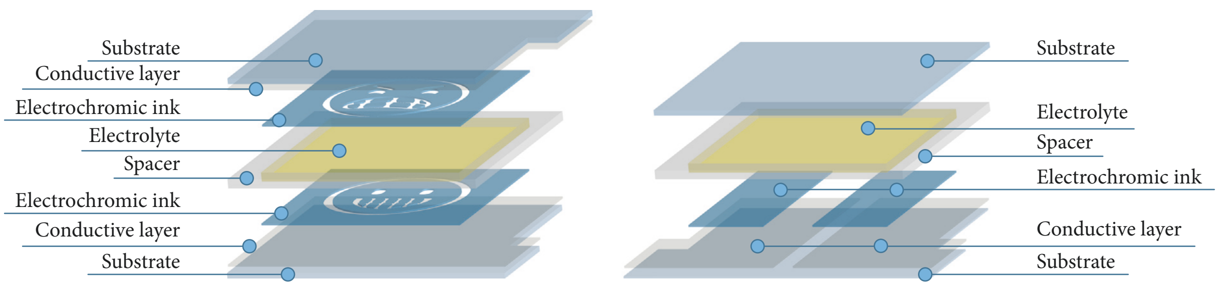

FIGURE 4: Composition of electrochromic technology. Vertical stack (left) illustrates how electrochromic ink is printed on two separate PET-ITO layers whereas coplanar (right) shows how the ink is printed on the same PET-ITO but with the ITO layer separated into isolated fields.

move when an electrical current is applied through the EC material. The electrolyte is a gel substance with electrically conductive properties and is responsible for the ion exchange between the two fields of EC ink when a voltage is applied at the conductors. Insertion or extraction of ions into the EC ink changes the optical characteristics through reduction and oxidization, and as little as 1V is sufficient for this change to occur. An EC system needs two fields of EC ink that are connected to two different conductors so that an exchange of ions from one field to the other can happen when a voltage is applied. One field will be oxidized while the other is reduced, and vice versa when the polarity of the voltage is reversed. Visually, this redox causes one EC field to become transparent while the other gains colour. Alternatively, one of the EC ink fields can also be replaced by any other ion storage material that does not exhibit colour change on redox, as shown in Figure 3.

While theoretically not needed for functionality, the display components need to be contained by elements that will insulate and protect them. Thus, top and bottom substrates are required. To be able to observe the visual change, at least the upper substrate should be transparent. Typically, glass has been used, but more recently, polymer-based plastics, e.g., polyethylene terephthalate (PET) and polycarbonate (PC), have been employed as well. In some implementations, the lower substrates can even be replaced with paper [42].

4. Prototyping TransPrint Displays

In this section, we present the design and fabrication process of TransPrint displays, which are transparent, flexible EC displays. This includes two alternative structures or stack designs, vertical and coplanar (see Figure 4), a detailed description of the fabrication process using screen-printing and inkjet printing as well as design considerations.

Firstly, TransPrint displays can be produced in two different ways: either a vertical or a coplanar stack of the different elements. In the vertical stack all elements are stacked vertically, meaning both electrodes with EC ink are on top of each other divided by the electrolyte (compare Figure 4 (left)). So that the ions would flow from the top layer EC ink through the electrolyte to the bottom layer EC ink or vice versa (when the polarity is switched). For the coplanar stack both EC ink fields are on the same layer with two separated electrodes (compare Figure 4 (right)). This means that the ions move from one of the EC ink fields to the other through the electrolyte. The main difference between these two construction methods is that in the vertical stack the ink fields, e.g., can overlap while in the coplanar stack they must be next to each other.

To create the construction highlighted in Figure 4 the TransPrint method uses the following materials:

(i) Substrate: PET-ITO

(ii) Electrochromic Ink: Ynvisible EC Ink (based on PEDOT:PSS)

(iii) Electrolyte: Ynvisible Electrolyte [43]

(iv) Spacer Material: double-sided tape 3M 9495 LE 300LSE

For TransPrint we selected to use transparent PET film as the substrates onto which displays are constructed. In the vertical stack configuration, one EC ink field is printed on both substrate layers, whereas in the coplanar stack, both EC

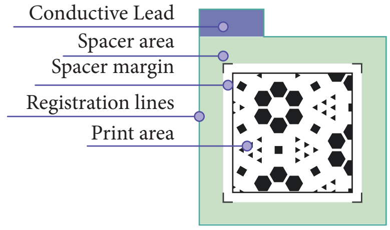

Figure 5: One side of vertical stack design example including spacer (green) and conductive lead (blue). A narrow margin is added between design and spacer material.

ink fields are printed on a single substrate. In both cases the two EC ink fields each have their own conductor and are connected only by the electrolyte layer. The EC ink used in TransPrint displays is itself conductive; thus it is only required to configure the conductors to connect to the edges of the EC ink fields. However, to reduce potential design limitations and ensure consistent switching performance, in TransPrint we utilize substrates coated with a conductive Indium Tin Oxide (ITO) layer which is one of the most commonly used transparent conductors and is also used as the conductor on smartphone touch panels.

Thus, TransPrint utilizes PET film precoated with ITO (PET-ITO) as substrates. For the vertical stack, both base and top layer are PET-ITO whereas for the coplanar structure PET-ITO is used for the base layer and noncoated PET for the upper layer. When using precoated PET-ITO where the whole piece is one conductor (e.g., the Adafruit ITO Coated PET (https://www.adafruit.com/product/1309) with a thickness of 175μm) for the coplanar stack, electrical separation of the two ink fields must be ensured, e.g., by scratching away the ITO coating from the PET to create a gap. Graphical display designs can be printed directly onto the ITO side of the PET-ITO using either screen- or inkjet printing. The PET-ITO material used is a thin film, which can easily be cut to different shapes, increasing the options for customization and flexibility of the displays. To prevent electrical short circuits between the top and bottom layers and to provide a container for the electrolyte, the PET-ITO substrate layers must be held apart.

In TransPrint this separation is created using double-sided adhesive sheets in which spaces have been cut out around the ink printed area, specifically 3M 9495 LE 300LSE, with a thickness of 170μm (see Figure 5). The amount of electrolyte required is calculated as the cubic volume of the container that is created between the two substrates and the spacer. For example, a display with a 5x5cm area using the previously mentioned adhesive sheets give the container a height of 170μm and therefore require 0.425mL of electrolyte (5cm x 5cm x 0.017cm = 0.425 cm^3 = 0.425ml). This means that the average amount of needed electrolyte is dependent on the size of the display.

Either inkjet or screen-printing can be used to transfer the graphical design onto the PET-ITO substrates. For rapid and precise prints inkjet is optimal; however, it allows for less control over the amount of EC ink deposited during the printing process which can potentially lead to lower quality prints. For both, inkjet and screen-printing we used PEDOT:PSS based EC inks supplied by Ynvisible Interactive Inc. (https://www.ynvisible.com/ec-kit). While not completely identical, we expect comparable results from PEDOT: PSS based inks supplied, e.g., by Sigma-Aldrich (https://www.sigmaaldrich.com/catalog/product/aldrich/483095). Screen-printing utilizes a stencil of the graphic design on a frame-mounted mesh to transfer the ink onto the substrate [25]. Screen-printing meshes have different thread densities, depending on how much detail is required, or how much ink has to pass through it. Additionally, the type of emulsion used to create the stencil affects the print detail. As an alternative to using emulsion, stencils may be cut out from vinyl.

Figure 2 shows the transition between the two maximum states of a vertical stack EC display, caused by the reversal of the polarity of the voltage applied across the display conductors. For this 5x5cm display the full transition takes approximately 2.5s. Applying power to the display for shorter times will place the display in an intermediate state where the maximum opacity is not reached. Switching time and required voltage are dependent on the EC design, size, and used ink and electrolyte. For the Ynvisible EC-SC ink a maximum voltage of 3V is recommended; however the ITO layer on the PET-ITO will degrade if a voltage of more than 1.5V is used, which in turn sets the maximum voltage for driving the display. Given these low voltage levels, the displays can easily be controlled using, e.g., an Arduino microcontroller, and could be even activated using wireless energy sources such as NFC, as demonstrated by Dierk et al. [44]. Furthermore, the active operation temperature of these displays' ranges from -100°C to +100°C and they continue to be functional after structural damage (e.g., a corner cut off) if the two conductors are not creating a short circuit. The displays are also bendable up to 7.5mm radius (see Figure 1) while remaining functional. The bend radius is limited by the fact that the ITO layer on the PET-ITO will break with a lower radius and thus increase the resistance. This also means that the mechanical endurance of the displays when repeatedly bends is only dependent on the quality of the PET-ITO. A bend radius of 0.75cm-1cm has been shown to have no influence on the resistance of the PET-ITO [45]. However, not only the bend radius is increasing the resistance of the PET-ITO but also repetitive bending as it leads to microcracks [46, 47]. Given results presented by Li and Lin it is expected that after ca. 300 bends with 17.3N strain the PET-ITO would reach a level were a significant increase in switching time would be visible and after 2000 bends being most likely be unusable due to the number of microcracks [47].

Furthermore, it should be noted that the printing of TransPrint displays does not require a completely dust free work environment. Although any dust particles etc. that made it onto the materials during the construction process will be visible on the display, they will not impede the display's functionality. Nevertheless, it is advised to work in an as clean environment as possible and use gloves through the whole procedure to not leave fingerprints on the display.

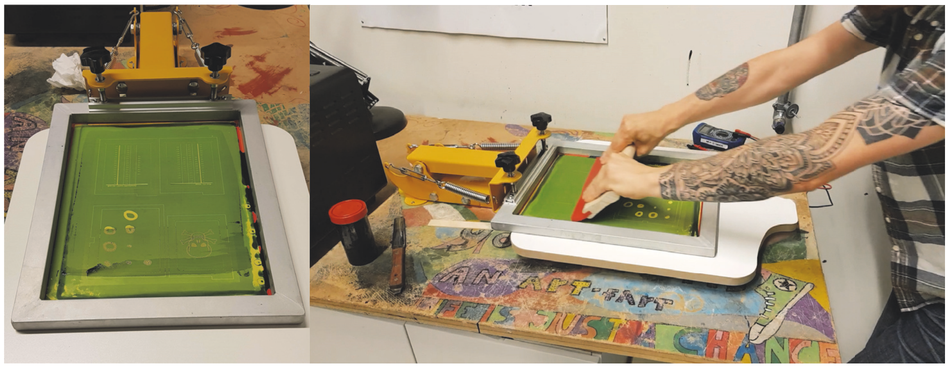

Figure 6: Left: screen-printing frame with exposed design. Right: screen-printing of EC displays.

4.1. Graphical Design. When designing the graphics for a TransPrint display several factors should be considered. Vertical stack structures have two layers overlaid on each other, allowing a large degree of creativity in how the finished display will look. In the coplanar structure, the EC fields should be next to each other, enabling the ions to move from one field to the other, placing more restrictions on the design. To partly address this limitation, opaque masks may be placed on top of the display; e.g., Klamka and Dachselt used a coplanar 8-segment EC display for their work, in which each segment in the display consisted of a pair of EC fields which were used [4]. In this case, one field was the visible segment of the 8-segment display, while the other served as a masked counterpart to complete the redox reaction.

If screen-printing is used, the frame count and emulsion determine the minimum size of both trace width and detail size; however there is no limitation for how big a trace or feature can be. The same applies when vinyl cutting is used to create a stencil; the accuracy of the vinyl cutter used must be sufficient for the level of detail in the design. Once the graphics have been developed, the design has to be finalized for print which requires adding registration lines for the spacer material (double-sided tape) and connections for the electrodes (see Figure 5). This step is especially important when designing for the vertical stack structure, as the conductive leads should be offset to avoid shorting the electrical circuit. If a vertical stack design uses superimposed graphics between the two layers, one side of the design should be mirrored to ensure it would be correctly oriented when assembled. The switching time of the display can be affected by altering the balance of the amount of ink between the paired EC fields, e.g., if both top and bottom layer have an equal amount of ink for insertion and extraction of ions the switching time will be equal for both polarities. Altering this equilibrium allows designers to create interesting and alternative transitions in their designs.

4.2. Display Printing. The process of screen-printing EC displays follows the normal screen-printing procedure and does not require any specific changes to the process (compare Figure 6). In Section 5.1 we discuss in detail the effect of different stencils and mesh counts. Most screen-printing equipment should be suitable for printing of TransPrint displays and, besides the graphical design of the fields, there are no limitations that affect the screen-printing of EC ink compared to any other ink. When using inkjet printing some details should be considered. Firstly, we recommend using a piezo-driven printer rather than a thermally driven one. As the EC ink is water based there is a risk that the heat of the thermal-driven printing alters the structure of the EC ink. Considering the amount of ink discharged, prior work recommends using the Brother brand of printers, as they have been shown to dispense larger amount of ink [2]. For our tests, we utilized a Brother MFC-J480DW with corresponding refillable cartridges, which provided excellent print quality. The Ynvisible inkjet EC ink has to be filtered before use, to avoid particles clogging the print head. Overall, inkjet printed displays have shown lower contrast ratios compared to screen-printed ones. However, inkjet printing provides the possibility of easily changing and adjusting the graphical design without the need to manufacture a stencil first. Therefore, it is very well suited for making rapid proof-of-concept prototypes. After the silkscreen or inkjet printing process the ink, coated PET-ITO must be heat-cured for 2m-3m at 120°. This is because the EC ink is water based which should evaporate before the display is assembled. For this either a small oven or a heat gun with temperature control is recommendable.

4.3. Display Assembly. After the EC ink has been printed on the PET-ITO, the first step in the assembly is to cut the PET-ITO and spacer to size (Figure 7(1)). If the cut lines did not get through the mesh during the screen-printing process, the negative mask can be used to mark where to cut. Afterwards the spacer material—double-sided tape—should be applied (Figure 7(2)). To help aligning the layers, the base and top layers should align and taped to the cutting board at one side, i.e., creating a hinge. This way the top layer can then be flipped over while maintaining alignment with base layer while the spacer is added to the base layer (Figure 7(3-4)). The cubic volume of the spacer cut-out should be calculated to identify the amount of electrolyte required. Using a syringe, the liquid electrolyte is then applied as a blob in the middle of the cut-out in the spacer, and the top substrate layer is flipped back over to cover it (Figure 7(5)). The electrolyte should then be gently dispersed to fill the spacer area using light pressure

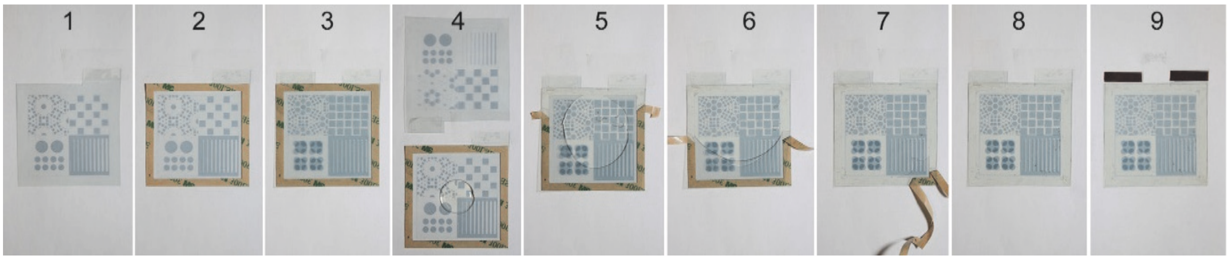

Figure 7: The different steps of the assembly process of a vertical stack TransPrint display.

in a circular motion while at the same time removing the spacer protection as it is dispersed. Firstly, the electrolyte will disperse towards the spacer wall midpoints. However, before the electrolyte reaches the spacer walls midpoint, the top substrate layer should be pressed to the spacer ensuring it adheres and preventing the electrolyte from being squeezed out. The electrolyte should then be eased into the corners of the space, ensuring it is evenly dispersed (Figure 7(6-8)). Finally, copper tape is applied to the conductive leads to improve conductivity (Figure 7(9)). Once the display is assembled, it should be cured under UV light for 25-30 minutes using a commercial 500W halogen spotlight. But basically, any lightbulb that emits UV can be used but will require different times [43]. The UV curing process solidifies the electrolyte to film instead of a liquid, making the display more robust. While this step is not needed, it is recommended to ensure a longer lifetime as well as prevent short circuits. A video overview of how to assemble the display can be found here: https://youtu.be/mi0p2VBo41s.

4.4. Integration of Capacitive Touch Sensing. Through capacitive touch input TransPrint displays can also be made interactive. As TransPrint displays are comprised of different conductive layers it is possible to sense a finger touching the display surface using capacitive sensing [48]. Specifically, the PET-ITO substrate provides excellent conductivity to be used as a touch surface to, e.g., control the colourization of the display. For our proof-of-concept evaluation, we utilized an off-the-shelf MPR121 touch sensor breakout board (https://www.adafruit.com/product/1982) connected to one of the two PET-ITO layers of a vertical stack display. While the MPR121 has on-board touch and proximity sensing capabilities including autocalibration and configuration for optimal sensing, we found that using the default settings on the MPR121 did not have sufficient sensitivity and therefore changed the charge capacitance to 63μA instead of the default 1μA. After establishing the basic ability to sense touch, we proceeded to test the sensitivity of different regions of the display. Differences in response across the display area were found to be negligible overall if the ITO layer has not been altered. Through alteration of the ITO layer—e.g., through scratching it away and effectively dividing it into multiple parts—several touch points can be created. It should be noted that, during switching, when power is being delivered to the display, touch sensing is not possible as the PET-ITO is being charged. Given that the display requires power for time periods of up to 2 seconds, this can be problematic. Therefore, we would advise to use time-multiplexing between power for switching the display state and sensing (similarly proposed by Olberding et al. [6]). The following cycle durations have been found working for the MPR121 and a TransPrint display: a display switch cycle of 10ms is followed by a sensing cycle of 5ms. This results in a frame rate of 67 Hz. This increased the time for a full display switch by 33% but allows for responsive touch sensing.

4.5. Display Contrast. One of the advantages of EC-based displays is their relatively low need for power. Once the display has been switched (either oxidized or reduced) into one of its states, it will stay in this state for a certain amount of time, while slowly fading to the neutral state. To investigate this fading contrast, we switched a TransPrint display into one of its states and captured pictures with constant illumination every ten minutes. We used a Canon EOS600D camera connected to a Raspberry Pi to capture the pictures. To quantify the temporal change we used the contrast ratio as a measure. The contrast ratio is defined as the ratio of the brightest colour compared to the darkest colour that the display can produce [49]. Usually it is measured between white and black, but as we used blue EC ink, we measure the contrast between an area of the display placed on a white background and the darkest blue tone on the display. As no standardized method existed, we employed an approach similar to Gentile et al. [50], the W3C defined method from the Web Content Accessibility Guidelines (WCAG) [51]. The WCAG uses the following definition of contrast ratio (C_r) between the text and background colours:

$$C_r = \frac{L_1 + 0.05}{L_2 + 0.05} \quad (1)$$

where L_1 is the relative luminance of the brightest colour, L_2 is the relative luminance of the darkest colour for which $1 \geq L_1 \geq L_2 \geq 0$. The definition of relative luminance L corresponds to the Y component of the colour in the CIE 1931 XYZ colour space [49]. Given the above formula the maximum C_r is 21 and the minimum 1. The WCAG suggest a minimum C_r of 3 for websites to be easily readable [49, 50]. We repeated the fade test for 10 displays printed with screen-printing using 80T frames and High Resolution-Diazo-Photoemulsion and calculated the C_r for these displays at 10-minute periods. The averaged fading can be seen in Figure 8. Directly after the displays have been switched into one of their states, the

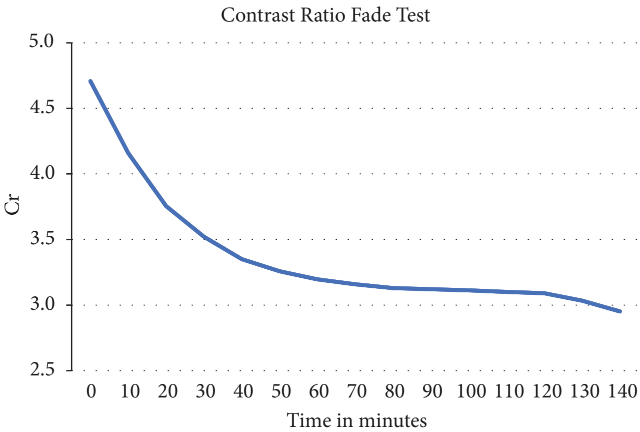

Figure 8: Development of contrast ratio after an EC display has been switched to one state.

C_r is very high at around 4.5 but after the first 20mins on average it already loses a significant amount of contrast, but nevertheless it stays above the minimum recommended C_r of 3 for over 2 hours. This demonstrates that TransPrint displays can retain an adequate contrast ratio for 2 hours before they need to be stimulated again. While this is not as lengthy as the retention time of e-ink displays [44], the possibility of fabricating them in a DIY manner and the ability to be transparent provides advantages that are unmatched by e-ink.

4.6. Display Lifetime. One of the important aspects of an EC display is its ability to switch between oxidized and reduced state and retain its visual details. However, this ability can fade after a number of switching cycles. Using a Canon EOS600D camera connected to a Raspberry Pi, 10 displays were subjected to a degradation test. The displays were switched 10000 times with a photograph of the display being taken every 100th switch. Each switch cycle consisted of a 2.5s time powered with 1.5V followed by a 2.5s rest period, followed by a powered cycle again of 2.5s with -1.5V and another resting period of 2.5s. During the resting period no power was applied. The displays did not exhibit any degradation and were able to fully switch after the completed test sequence. However, after 10000 switches the switching time needed to fully excite the display increased and to fully transfer to one state had increased to 3.5s compared to 2.5s prior to the test. The changes were visible after 4200 changes and linearly degraded. However, it should be highlighted that no changes in terms of contrast ratio were found if the displays were fully excited. These findings demonstrate the durability of the TransPrint displays but highlight that the switching time needs to be potentially adapted over time. TransPrint displays only require power during switching; once the display transition is completed, continued electricity will permanently damage the display. At this point we would like to stress that the production of these displays is a manual process, the display quality can vary drastically, and detailed analysis of the displays would be subjected to large deviations.

4.7. Power Consumption. EC-based displays have a low-power consumption and only require to be powered when switching between the different states of the display. However, the exact amount of energy consumed by an EC display to switch depends on a variety of different factors. The main factors are the size of the displays as well as the amount of ink that has been used. In addition, the amount used electrolyte and the quality of the ITO coating on the PET potentially affects the energy consumption. To give an estimate of the power consumption, we measured the consumption of a set of displays. We used an Agilent 34450A Multimeter and the corresponding software for it. We tested three different displays; 5x5cm Evaluation Design printed using inkjet printing, 5x5cm Evaluation Design printed using an 80T frame with high-resolution emulsion, and a 10x10cm honeycomb design (compare Figure 10 printed using an 80T frame with high-resolution emulsion). For each of these displays we used a switching time that was just long enough to fully complete the visual transition. We then calculated the average power requirements over five switches for each display. For the inkjet display, the switching time was 1.1s, with an average current draw of 2.72mA, resulting in a power consumption of 4.3mW per switch. The screen-printed 5x5cm display took 2.4s to switch and had an average current draw of 2.6mA, which resulted in a power consumption of 3.8mW. Lastly the screen-printed 10x10cm display had a switching time of 5.1s and an average current draw of 4.9mA, resulting in a power consumption of 7.8mW. These values well demonstrate the low-power consumption of TransPrint displays.

5. Best Practices

In this section, we report on best practices for producing high-quality EC-based displays using the TransPrint method. Our overview of best practices and expected outcomes are based on the authors' experiences from printing several hundred displays using this method.

5.1. Print Quality. As the amount of EC ink applied to the PET-ITO affects the maximum levels transparency and colourization of the final display, here we provide an overview of the influence of mesh count and vinyl stencil placement in terms of ink dispersion. For detailed prints it is important to ensure that high details are retained from the original digital design through to the final print. As the emulsion type dictates the amount of detail retained during the exposure, we investigated two different types of emulsion. Furthermore, we also give an overview of results that can be achieved of vinyl stencils, which are a viable option for screen-printing. For emulsion-based prints, the digital test design was printed to fill an A4 exposure film. An example of the digital design for test and assembled display in balanced and powered state can be seen in Figure 9. Photographs of the displays were taken before and after applying power (1.5v and -1.5v). To keep to the off-the-shelf viability of fabricating EC displays we bought a screen-printing starter kit that contained a 55T frame, hybrid photoemulsion, and press. A starter kit of this kind is the fastest way to get into screen-printing as it contains all the materials required to get started. Additional 80T and

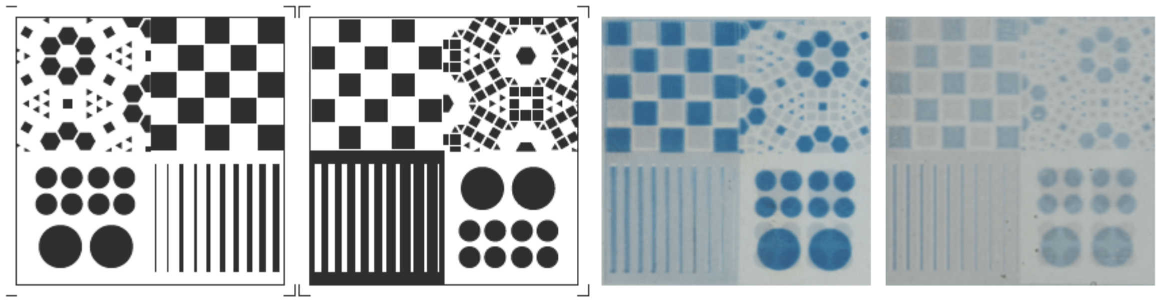

Figure 9: *Left*: digital design used for evaluating different parameters during screen-printing. *Right*: difference between displays printed using a 80T frame with high-resolution emulsion and inkjet printing.

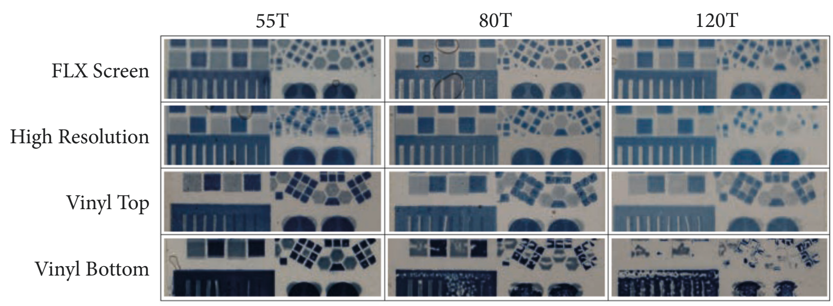

Figure 10: Images of powered displays arranged by thread count and stencil type.

120T frames and a high-resolution emulsion were bought for testing. All prints were made using 125μm PET-ITO (40-60 Ω), 230μm double-sided tape sheet spacer, and Ynvisible EC-SC ink and electrolyte.

The screen-printing parameters compared were

(i) Frame mesh count (55T, 80T, and 120T Frame)

(ii) Emulsion type (FLX Screen-Hybrid-Photoemulsion (https://www.siebdruck-versand.de/Siebchemie-Emulsion/FLX-SCREEN-Hybrid-Fotoemulsion-One-Pot/Allround::1065.html) and High Resolution-Diazo-Photoemulsion (https://www.siebdruck-versand.de/Siebchemie-Emulsion/HIGH-RESOLUTION-Diazo-Fotoemulsion-Diazo/Plastisol::820.html))

(iii) Vinyl stencil placement (On bottom of mesh and on top of mesh)

There is a difference in the preparation time between using vinyl stencils or emulsion stencils. While emulsion requires several hours of drying and washing out, as well as exact exposure when the prints are transferred from the negative, preparing the cut-out vinyl requires a lot of manual labour depending on the amount of details that have been cut out. Depending on ones' knowledge of these techniques, times can vary. Nevertheless, both approaches will take longer compared to inkjet printing. However, as the inkjet ink needs to be more liquid than the screen-printing ink to be properly dispensed, inkjet prints generally result in lower maximum colourization. Therefore, inkjet printing is recommended for proof-of-concept prototypes, while screen-printed displays present a quality ehich are suited for longer-term usage.

Many factors affect the quality of the assembled display, including scratches and fingerprints created during the assembly process. However, here we disregard these production defects and specifically focus on the quality of the print regarding transparency, colour, and detail. The following factors were noted as affecting the display print quality:

(i) The thread count of the frame has a very eminent effect on the maximum transparency and colourization of the displays, see Figure 10. A lower thread count will allow for a higher ink dispersion onto the PET-ITO.

(ii) The FLX screen emulsion produced consistently good results. The high-resolution emulsion resulted in similar results in terms of the amount of inks dispersed but with slightly higher details. Using 80T or 120T with high-resolution emulsion produced the best results in terms of details and transparency.

(iii) When the vinyl stencil was mounted on the top of the mesh, the results are comparable to the FLX screen emulsion print. However, due to the limits of a vinyl cutter, fewer details are possible. For a vinyl stencil placed below the mesh, only a thread count of 55T produced prints of viable detail. However, the amount of ink dispersed was so high that the ink in its reduced transparent state was still strongly visible. The other two thread-counts consistently produced unusable results.

A general challenge with the vinyl stencil was that during the transfer of the vinyl to the frames small standalone details can easily fall off.

5.2. Discussion

5.2.1. Transparency. An important characteristic of TransPrint displays is their transparency, and we experienced different levels depending on the printing process and materials used. One of the main influencing factors is the used PET-ITO. While the aforementioned Adafruit PET-ITO only has a very thin layer of ITO and is therefore highly transparent, other PET-ITO supplies we tested created a visible yellowing of the displays. The electrolyte [43] on the other hand has very little influence. Thinner layers of EC ink result in higher transparency when the ink is in a reduced state, but consequently result in a lower opacity when excited. Depending on the application case for the printed display, different approaches to printing will be optimal. For example, in a case where only limited transparency is needed but high colourization is required, a lower thread count and perhaps a vinyl stencil should be used to print the display. If the display requires a high transparency, a higher thread count with using screen print emulsion or even inkjet printing should be favoured. Being able to vary the thickness of the layer by utilizing different mesh counts in the screen-printing process allows for more diversity in the design. The usage of vinyl as a stencil material is possible; however it should be placed on the top of the frame and a frame with a higher thread count should be used to get more usable results. Moreover, vinyl stencils only work acceptably with low detailed graphic designs. The high amount of ink dispersed when vinyl is placed on the bottom of the screen is most likely due to the thickness of the vinyl allowing a larger amount of ink to be deposited.

5.2.2. Ease of Design and Fabrication. A major challenge in the design of TransPrint displays is that the designer will only know how a display transition will look like once the final print is done. So far, no software to simulate and visualize these changes exists. Especially, in vertical stacks, where the printed layers are on top of each other, the maximum transparency of one layer can still influence the visibility of the other layer depending on the way they have been printed. Also creating a design where the amounts of EC ink in each field balance, to ensure optimal performance, can be challenging when designing such displays.

For smaller displays of less than a 9cm display diagonal, the production can be relatively easy managed by a single person. For larger displays with a larger diagonal size, it is helpful to have a second person available during the display assembly to help avoid bulges and misalignment of the PET-ITO on the spacer material. Such assembly faults can create areas where the two ITO layers touch, thereby creating a short circuit in the display. Air bubble in the electrolyte during assembly is another potential problem. Such bubbles can be partially alleviated by applying a circular motion when spreading the electrolyte, slowly distributing the electrolyte, and creating a seal by pressing the PET-ITO firmly onto the spacer. However, for bigger displays the difficulty of this fabrication step increases and air bubbles are easily introduced (see Figure 11). Nevertheless, there is no limit to the potential size of displays produced with the TransPrint method. However, larger displays have a significant higher switching time, e.g., an A4 printed display takes between 8 and 10 seconds.

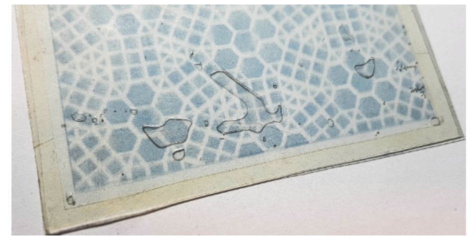

Figure 11: Example of 10cm x 10cm display assembled by one person with air bubbles in the print.

While it is theoretically possible to create matrix displays using electrochromic materials [30] as well as with the TransPrint method, we would argue that those are not the strong points of this method. Given the needed connections for the different fields it would result in proper distances between the fields which in turn would not be very aesthetically pleasing.

5.2.3. Coplanar and Vertical Stack. The two stack structures supported by TransPrint each bring advantages and disadvantages, allowing for a high diversity in types of displays. The vertical stack allows for superimposed graphics that can switch between the two layers. If an equal switching time is required for the display, both layers should have near the same amount of EC ink applied and the EC parts should be close together to allow the oxidization and reduction to happen as efficiently as possible. By adjusting the switching voltage level (in the range 0-1.5v), the amount of EC ink, and the placement of the graphics opposite each other it is possible to create different visual effects during the display switching.

For coplanar stacks, the design can be more challenging, as the distance between the fields can prolong the switching time drastically. This can be used to create different switching effects but is normally not preferable. The main problem with this structure however is the need for nonconnected conductors. While in advanced print processes, connections to the EC fields could be printed with conductive ink, instead of an ITO covered surface, this complicates the prototyping process drastically. Scratching the ITO of the PET-ITO surface is a faster method that can be applied after the EC ink is dried relatively easily but is more limited.

6. Application Examples

In this section, we present different application scenarios and ways to utilize TransPrint displays. We present six examples: a switchable logo, a context-adaptive timetable, touch sensitive transparent buttons, an interactive paper map overlay, a wireless powered game card, and interactive art.

Figure 12: Application examples. Left: changeable logo. Right: changeable time plan.

Figure 13: Application examples. Touch sensitive transparent buttons mounted on a window.

All the displays were printed using screen-printing with the following materials: 175μm PET-ITO, 130μm 3M spacer, Ynvisible EC-SC ink, and Ynvisible electrolyte. As a limitation of the ITO, the maximum voltage for these displays is 1.5V unless otherwise stated. Higher voltages will degrade the ITO layer and eventually render the displays nonfunctional.

6.1. Switchable Logo. The first application case is a switchable logo for a glass. It demonstrates several of the unique capabilities of EC displays. It is a transparent and nonrectangular display—here in form of a circle—that is bent around a glass; see Figure 12 (left). The display is fabricated as a vertical stack and demonstrates a switch between two different graphics that, for example, can highlight different properties of a product, here the fact that the beer is Natural and Premium Quality.

6.2. Context-Adaptive Timetable. Static bus timetables typically have times printed for both weekdays and weekends on the same sheet of paper, taking more space than needed and confusing the reader. With a vertical stack design it is possible to print the two timetables overlapping and only show the relevant times when needed; for example, the weekend schedule would only be shown on weekends; see Figure 12 (right). In this application, TransPrint displays have an advantage compared to EL and OLED displays, that they do not emit light and therefore are not subject to, e.g., public legislation with respect to street lighting. This make them well suited to replace such paper-based public displays with more interactivity in the future.

6.3. Touch Sensitive Transparent Buttons. Several previous attempts have explored how transparent displays can support colocated work on a shared visual workspace [52–54]. However, these approaches often required complex display technologies such as LCD [54]. We believe that EC ink displays can be used for fast and cheap prototypes in this area as well. We printed a set of touchable buttons, e.g., to control a media player (compare Figure 13), that can be attached to a variety of surfaces. For touch sensing we use an MPR-121 breakout board, as described above. User interface elements that only express minimal change such as the here shown music player controls or simple switches are perfect examples how TransPrint displays can be used as interactive graphics that allow to be fitted on a variety of existing objects without altering their aesthetics significantly. However, if needed they can be used to alter the experience. For example, the different levels of transparency that EC displays offer can alter the appearance, e.g., similar to the work of Lindlbauer et al. [55].

6.4. Interactive Paper Overlays. The last three application cases make all use of the same principle, they take advantage of the fact that TransPrint displays are transparent and can therefore be combined with already existing static printed materials. To demonstrate these retrofitting capabilities we created three examples: an interactive paper map overlay (see Figure 15), a wireless powered game card, and interactive art (see Figure 14).

The interactive art piece aims to spur discussion around the possibilities of EC displays in the STEAM movement, as well as to demonstrate the creation of animations using EC transition times. The basis of this work is Kandinsky's Farbstudie Quadrate, where parts of the art have been cut-out and left white. These parts have then been printed on a coplanar stack EC display with two separate EC fields created by scratching the ITO layer so that it forms two electrodes. The assembled display is overlaid on the original art piece.

Figure 14: Application examples. Left: interactive art. Right: interactive game card.

Figure 15: Application examples. Interactive map overlay showing two different walking routes.

Instead of using the usual switching voltage of 1.5V, a lower voltage such as 0.5-0.8V is applied, resulting in a slower transition time. This slow transition time creates the illusion that the art is alive and changing.

The low voltage requirements of TransPrint displays make it possible to power them using, e.g., NFC, solar power or wireless charging. This could be applied similarly to the work presented by Dierk et al. [44]. We envision this could be used for example to create interactive game-cards in combination with technologies such as Project Zanzibar [56]. Our example overlays a skull on a regular game card to indicate if the card has died in the game. For powering the game card we used the MikroElektronika NFC Tag 2 click. A smart phone's NFC chip is providing sufficient power to change state of the display. For this display we used a vertical stack design; however we left out the second EC field and instead used the ITO layer of the PET-ITO substrate that was not printed on as the second ion storage.

The final example is an interactive overlay for a paper map, where, e.g., bicycle riders can press a button to select a path that is then highlighted on the map. As with the interactive art piece we used a coplanar print with the ITO layers scratched to form two conductors. For such an outdoor situated display, e.g., solar power with rechargeable batteries could be used to enable deployment the display nearly anywhere. Note also that no additional electrical wiring is required to provide interactivity.

7. Conclusion and Future Work

TransPrint is a method to print custom flexible transparent free-form electrochromic (EC) displays, which allows non-experts to easily create displays for use in HCI applications. The created displays are nonlight-emissive, making them suitable for seamless integration into a variety of environments, without the disruptive light output of other display technologies. We have detailed the process to design and construct TransPrint displays, highlighting best practices and the benefits of alternative approaches. TransPrint displays are created using common screen-printing or inkjet printing methods, together with a lightweight assembly process. Capacitive touch sensing can be seamlessly integrated into the displays without the need for additional sensor wiring. The example TransPrint displays created maintain their display state without power for 2 hours and have low-power consumption, requiring less than 4mW to switch state. The potential application space for TransPrint displays has been demonstrated by the construction of five prototypes. Our contribution extends the tool set available for the maker community enabling designers and creators to rapidly functional devices with a minimal overhead. For future work, we want to develop a software stack that will enable designers to simulate the visual qualities of the display before the display is printed. In addition, plugins that will support the designer while designing these displays, e.g., by showing the area of the different EC ink fields would be beneficial. Furthermore, we want to explore more prototyping techniques.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

A video overview demonstrating the printing and assembly process as well as the working prototypes. *(Supplementary Materials)*

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