Screenprinting and TEI: Supporting Engagement with STEAM through DIY Fabrication of Smart Materials

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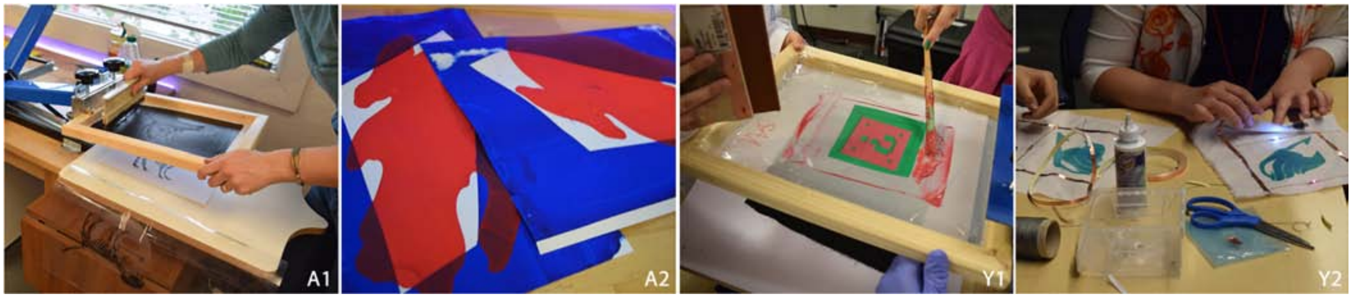

Figure 1. Screenprinting with conductive ink and thermochromic prints on paper developed during our art workshop with adults (A1 & A2); children screenprinting and assembling foldable circuits on fabric during our STEAM class for junior highschool youths (Y1 & Y2).

ABSTRACT

This paper focuses on manual screenprinting as a DIY fabrication technique for embedding interactive behavior onto a rage of substrates such as paper, fabric, plastic, wood, or vinyl. We frame screenprinting as a process that operates at the intersection of art, technology, and material science and iteratively examine its potential in two STEAM contexts. We conducted youth and adult workshops whereby participants worked with our low-cost thermochromic, UV-sensitive, and conductive screenprinting inks to develop a range of concepts and final projects. Our findings highlight several unique features of screenprinting: it affords a low barrier to entry for smart material fabrication, supports a collaborative maker practice, and scaffolds creative engagement with STEAM concepts. By being widely-accessible and substrate-agnostic, screenprinting presents exciting opportunities for TEI: DIY fabrication of smart materials in domains such as fine arts, information visualization, and slow technology; and bridging diverse disciplines through STEAM screenprinting initiatives at youth and adult levels.

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Author Keywords

Screenprinting, DIY fabrication, STEAM, smart materials.

INTRODUCTION

Recent HCI research has innovated a number of printing methods to create interactive materials such as printable touch sensors, biosensors, hydrogels, and thin-film displays [27, 38, 43]. This work has contributed towards the evolution of "smart" materials, whereby instead of using external components, responsive behavior and/or visualization is incorporated into the material itself. In this paper, we focus on screenprinting as a DIY fabrication process that can be used to embed interactive properties into a range of substrates including paper, fabric, vinyl, wood, or acrylic.

We focus on screenprinting not only because it has not been previously studied widely in HCI literature, but also because it has several unique advantages. First and foremost, screenprinting is extremely versatile as it can be applied to a variety of substrates. Second, screenprinting supports different stencil-making methods: the images to be printed can be created by vinyl cutting, hand-drawn with screen filler and drawing fluid, or developed with photo-emulsion, to name a few. Because of its versatility, screenprinting also has a low barrier to entry. DIY-level screenprinting set-ups are accessible to amateurs and screenprint designs can be easily replicated and altered. When coupled with interactive or conductive inks, screenprinting operates at the crossroads of traditional art practice, technology, and material science. Therefore, when framed as a DIY fabrication method for smart materials, screenprinting presents a novel platform for creative STEAM initiatives in TEI.

Research Contribution

Our work applies manual screenprinting to support DIY fabrication of smart materials in STEAM contexts. We begin by describing the low-cost screenprinting inks we developed, which demonstrate consistent reproducibility of photochromic, thermochromic, and conductive properties across different substrates. We then present findings from iterative STEAM workshops with adult and youth makers. In our adult workshop, local artists experimented with our screenprinting methods and applied them to their practice. The workshop resulted in two interactive pieces showcased at a local gallery and revealed a host of application areas for interactive arts, ambient displays, and ultra-low-cost sensing. Insights from the workshop led us to develop a summer camp course for junior highschool youths. Our key contribution lies in uncovering unique features of screenprinting when compared to other methods of making with responsive inks. We found that due to its reproducibility and versatility across almost any substrate, screenprinting supports a highly collaborative maker practice and naturally integrates the arts with science and technology. We conclude with broader implications for screenprinting as a DIY fabrication method for smart materials and a platform STEAM engagement.

RELATED WORK

HCI has been exploring the intersection between art and technology through venues such as the ACM Creativity and Cognition Conference, the Art.CHI workshop series [2], a DIS workshop on multidisciplinary participation [48], or this year's TEI Arts Track. Printmaking has been of particular interest in design research, with digital and analog technologies being used to embed prints into a variety of mediums [3], or serigraphy being proposed in a number of capacitive touch-sensing projects [22, 43]. Our work with screenprinting is especially aligned with two related work domains: smart material fabrication and STEAM.

Smart materials and DIY fabrication

Smart materials perceptibly change in response to their environment and recent HCI examples include odor, color, and shape-changing substances that visualize pH [26], a flexible and stretchable sensor network in the form factor of tape [15], stretchable proximity sensors [51], moisture-sensitive garments [51], and shape-changing foods [50], haptic interactions with piezo-resistive sensors [19], as well as new liquid-based and hydrogel printing technologies [49]. In most of these cases, however, specialized domain knowledge or equipment is needed to create these materials. Screenprinting presents a low-cost and widely accessible platform for embedding responsive elements onto a range of substrates—from wood to fabric, vinyl, and paper.

Similar to our work, recent DIY fabrication methods have incorporated paper into a range of interactive computing projects [5, 22]. Existing techniques include hacking Inkjet printers for rapid prototyping of electronics [27], using consumer level printing methods for fabricating interactive components [38], screenprinting with off-the-shelf conductive paint [7, 22], or painting circuits by hand [10, 13]. In addition, thermochromic inks have been used to produce ambient display technologies [36, 37] with external heating elements such as peltiers. Our work with screenprinting extends these techniques by embedding interactive elements as printed layers on a range of materials and exploring the versatility of the process with adult and youth makers.

STEAM initiatives and HCI

Our research integrates practices from the fine arts with fabrication of interactive and smart materials, and we orient our work within the STEAM movement. STEAM (STEM + the Arts) incorporates art and design into science, math, technology, and engineering fields, particularly in K-20 education [45], and has been backed by methodological HCI research [6, 18, 47]. STEAM principles have been implemented many computer clubhouses, which focus art and design through technology use [e.g., 25, 40, 41], and embraced by platforms such as Scratch [40], Robot Diaries [32], Modkit [33], LilyPad Arduino [9, 10, 16, 31], and EduWear [28], to name a few. More recently, STEAM research has explored sketching [11, 29], theatrical performance [24], music remixing [17], and sound composition [20], as platforms for science and tech learning. We contribute to this work by focusing on screenprinting—a previously unexplored approach in STEAM, which combines traditional printmaking, digital design, and fabrication of interactive materials.

ABOUT SCREENPRINTING

Screenprinting is one of the most popular DIY printing methods, which has been, for many years, used to produce static visual representations in various scales and forms. In this method of printmaking ink is transferred through a mesh screen onto an underlying material. A stencil on the screen makes sections of the mesh impermeable to the ink, thereby creating the desired patterns on the substrate. Screenprinting studios range from basic, at home DIY setups to professional level studios. Our screenprinting set-up is lower cost and could be easily implemented in makerspaces or private art studios and homes. Our process is fully manual process, using materials such as vinyl stencils, polyester meshes, off-the shelf inks, and several powdered pigments that are easily available for affordable prices (below $50).

To develop robust thermochromic, photochromic, and conductive screenprinting inks, we relied on expertise from our entire multidisciplinary research team, which included a screenprinting expert, a computer engineer, a biologist, and an interaction designer. Below, we describe three types of interactive screenprinting inks we developed: resistive, thermochromic, and UV-responsive. These were tested by

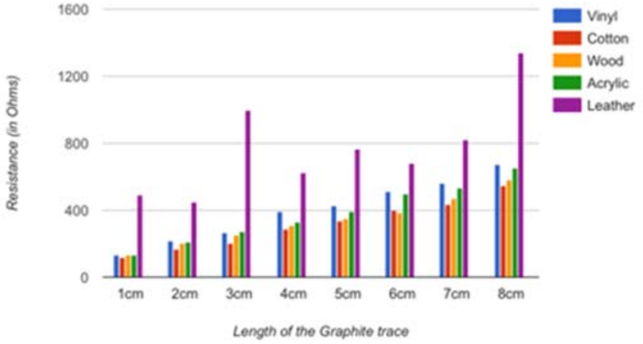

Figure 2. Resistance values of graphite traces printed on different materials (Average values of 2 samples of each material)

all members of the team to examine the reproducibility of the work by non-experts.

Low-cost, consistent resistive traces

There are many off-the-shelf conductive inks available for screenprinting, with resistive, (e.g., graphite-based) inks costing upwards of $18/oz [3] and conducive (e.g., silver-based) inks costing upwards of $60/oz [30]. Since screenprinting usually uses a large quantity of ink than hand-drawn or inkjet printed circuits we developed our own, ultra low-cost custom-made ink. The ink was made by mixing Graphite powder (General's pure powdered graphite), extender base (Speedball screenprinting gel polymer) and water at a 8:1:1 ratio by volume, costing under $2 per oz. We tested the resistance of graphite traces screenprinted on various materials including wood, leather, vinyl, and paper and measured resistance values across the ends of traces. Traces of similar length produced consistent resistance values on evenly-textured materials (except leather, which has an uneven surface) (Fig 2). Overall, this shows that screenprinting is a reliable method for embedding conductive traces onto woods, acrylics, and fabrics—substrates that have not been previously explored by prior research, which focused predominantly printing circuits on paper [22, 27].

Thermochromic prints

While our conductive inks can of course be paired with traditional electronics components (e.g., LEDs, sensors, etc.) to prototype interfaces, we also examined thermochromic actuation as a form of expressive output. Thermochromic pigments are heat sensitive compounds that temporarily change color with exposure to heat. There are many commercially available powders with different color choices and temperature sensitivities [17], and in our work we used pigments from [46] that change from color to clear at 77F. For screenprinting, we mixed these powders with extender base and water at a 10:1:1 ratio by volume. To confirm consistency, we tested the response of our prints to voltage actuation. We used 2 samples, where a thermochromic layer was printed on top of a graphite layer on 163GSM paper (Fig. 3). When voltage is applied across the graphite layer, it heats up causing the thermochromic layer to become clear. For the purposes of our tests, we used a voltage of 20V, kept ON for 1 minute in the beginning of the test and turned OFF for 5 minutes until the samples returned to their original colors. Color changes were video recorded using a Canon 550D DSLR camera at 60FPS with controlled lighting. Every 60th frame of the video (one data point per second) was read into the Matlab video reading function. Average RGB values of a 250-pixel square at the center of each selected frame was calculated using Matlab Image processing toolbox (Fig. 4). Our overall findings demonstrate consistent RGB responses in both samples.

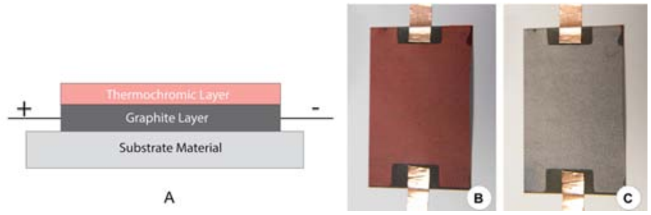

Figure 3. Thermochromic prints (A) Composition of printed layers (B) Normal state (C) After applying a voltage

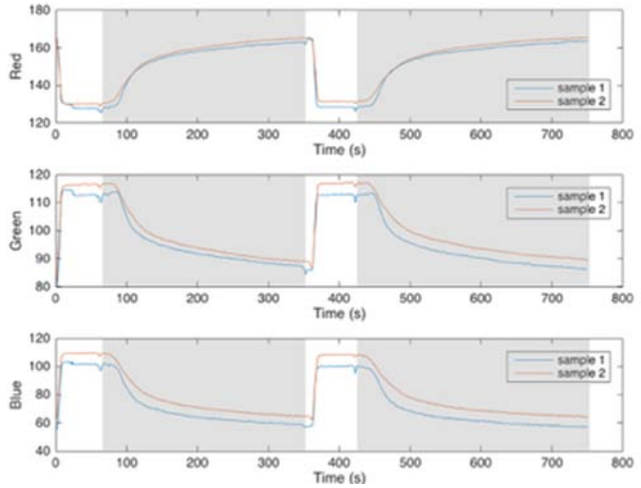

Figure 4. R,G and B values(0-255) of each samples against time (Shaded area = Voltage supply OFF)

UV sensitive prints

Photochromic pigments change color when exposed to an ultraviolet source (e.g., sunlight or UV flashlight). As with the thermochromic powders, there are many commercially available options with varying color changes. We used "solar drops"—concentrated liquids—that change from white to a color (e.g., white to red) when exposed to UV. We made UV-sensitive screenprinting ink by mixing solar drops with extender base [42] in 40:1 ratio by volume. We tested 4 samples printed on 90GSM paper, mounted on a

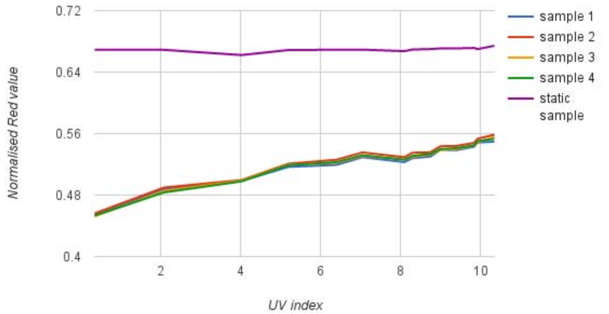

Figure 5. Normalized Red values against UV index reading

panel along with an Adafruit SI1145 UV index sensor [1]. A red piece of paper also mounted on the panel was used as a control color for calibration. The panel was placed in a stationary outdoor location that was exposed to natural sunlight. Photos of the samples were taken at different times of the day using a Canon 550D DSLR camera with a 17-55mm f2.8 lens in full manual mode at f5.0, 1/200, 200 ISO and 50mm. UV index sensor readings were recorded each time the photos were taken and all images were RGB normalized. Using the same MATLAB libraries as in the thermochromic set-up, average Red values were calculated for 250-pixel squares from the center of each sample (including the static red color paper). Overall, our findings demonstrate a consistent R-value response for all 4 samples at different UV levels, and a near-linear relationship between normalized Red value and the UV index (Fig. 5).

In summary, we used a fully manual screenprinting process and ultra low-cost, homemade inks to produce consistent thermochromic, UV-sensitive, and conductive prints. We continue to examine the potential of screenprinting as a DIY fabrication method in two STEAM contexts: a workshop with adults from arts community, and summer camp course we developed for junior highschool students.

SCREENPRINTING WORKSHOP WITH LOCAL ARTISTS

To explore how our interactive screenprinting inks might be applied in art domains, we conducted a workshop with 5 local artists (2 male) who were interested in interactive screenprinting techniques. Participants were recruited from various art disciplines, ranging from printmaking to dance, sculpture, and photography. During the workshop, which lasted about 4 hours, participants were presented with an overview of our inks and shown basic electronic concepts (e.g., connecting LEDs and switches to a battery using the Circuit Scribe kit [13], connecting battery powered heating elements etc.). Most of the time was used as an unstructured work session, whereby participants experimented with the inks, made prints, and provided feedback on how these materials could enhance their practice.

The workshop resulted in two finished pieces (Fig. 6) that were showcased at a Mixed Medium-themed art exhibit at a local gallery, drawing interest from the general public. These pieces consisted of heat-sensitive screenprints, heating elements and simple electronic circuits, which were introduced to the participants at the workshop. In addition, we audio-recorded the informal conversations that happened naturally during the work session. Transcription of the audio recording together with notes taken by the researchers were open-coded, and emergent themes were affinity diagrammed to reveal two application areas.

Figure 6. Workshop outcomes: participants' thermochromic prints with electronic heat actuation, showcased at local gallery.

DIY fabrication of smart materials

In our workshop, participants were able to replicate consistent photochromic, thermochromic, and conductive prints on materials ranging from paper, to fabric, wood, and acrylic. Interestingly, the participants viewed these resulting materials—and not just the prints—as interactive. While participants were aware of commercially available thermochromic and photochromic products, all participants noted that the ability to customize visual designs and print it on any substrate material would essentially enable them to create their own smart materials to incorporate into their art practice. The discussed ideas included: screenprinting interactive costumes for dance performances, making temperature-responsive sculpture installations, augmenting indoor spaces with prints that were actuated at different times of the day based on sun exposure, and combining screenprinted circuits with traditional photography to create touch-sensitive and responsive images.

In addition to these art domain-specific ideas, participants also discussed how DIY smart materials could aesthetically respond to the environment or visualize information. For instance, as screenprinting can be done on a range of substrates, participants suggested location-specific visual expressions (e.g., solar-sensitive designs in areas that received varying levels of sunlight to produce unique visual experiences throughout the day). Likewise, when working with the voltage-actuated conductive-thermochromic prints, participants discussed the ability to break away from the constraints of premade electronic components (e.g., screens or LEDs of fixed size) and suggested various ambient displays that would more aesthetically "blend" into the underlying material. These ideas were particularly inspiriting to the interaction designers on our research team, and working with one of the artists after the workshop, we rapidly prototyped two potential application areas for TEI: a printable ambient display and a low cost UV indicator.

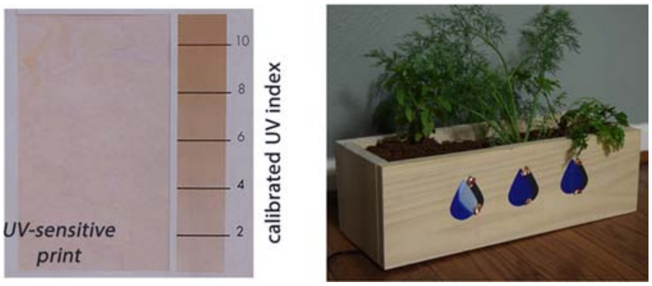

Figure 7. Rapid prototypes inspired by our workshop: screenprinted ultra low-cost UV indicator and non-emissive soil moisture display.

Printable ambient displays

Drawing on discussions from the workshop, we wanted to explore how new types of replicable information displays could be printed directly on materials such as woods, plastics, or textiles. To demonstrate this idea, we developed a rapid prototype that visualizes soil moisture on a wooden plant tray (Fig. 7). Data from a moisture sensor [44] embedded in the soil is processed by the Arduino microcontroller. Blue thermochromic water droplets printed over a graphite resistive layer directly on the tray are actuated, effectively changing from blue to white as the soil dries. Reflecting on this prototype, our team was particularly intrigued by the inherent slowness of thermal actuation. Unlike the near-instant response rates of most digital displays, the slow transitions between thermochromic colors mimicked the slower organic processes taking place inside the plant tray.

Printable UV indicators

Drawing on our participants' ideas to create location and time-specific prints, as well as the fact that our inks and methods produce consistent UV responses, we developed an ultra low-cost, printable UV index indicator (Fig. 7). By utilizing the results of our earlier analysis of UV sensitive prints, we found this indicator to be accurate when cross-referenced with the Adafruit UV sensor. While our rapidly-prototyped visual design is rather simple, future designs could more aesthetically engage viewers with UV exposure in different locations (e.g., murals on buildings) or on an individual level (e.g., prints on personal items).

Screenprinting as a platform for STEAM

In addition to applying interactive screenpring methods to their own practice, participants suggested using our inks and methods to teach art and science. Being from the fine-arts community, participants themselves used the workshop to learn about and experiment with simple heating elements (eg: DC powered heating pads, muscle wires) to actuate their heat sensitive screen prints. These explorations resulted in discussions around screenprinting as a way of integrating art and engineering activities. For instance, participants suggested a different workshop for novices to learn both printmaking techniques and circuit design through the use of thermal and conductive inks.

The accessibility of DIY screenprinting and the interest shown by our participants to work with electronic components suggests screenprinting as an entry point for STEAM. We continue by examining this direction through a youth summer camp course we developed.

STEAM COURSE OF JUNIOR HIGHSCHOOL YOUTHS

We developed a week-long summer camp module for junior highschool youths as part of a Digital Culture outreach program at our university. The camp teaches a breadth of creative skills, ranging from digital music design, to programming for games, and DIY fabrication using makerspace tools (e.g., 3D printing, laser cutting). Our module consisted of a 2-hour long class that ran Monday-Friday and for each project, students used low-fidelity sketching to brainstorm ideas individually and then worked on designing and screenprinting the chosen project in groups of 3 or 4.

Course curriculum

During the first day, students explored photochromism by mixing UV-responsive pigments with screenprinting inks and observing the colors with a UV light and sun exposure. Students also worked in groups to set up screens from pre-cut vinyl stencils and made their first prints using the photochromic inks they created. Days 2 and 3 focused on basic electronic concepts and students worked on designing their own stencils in Adobe Fireworks and screenprinting a folding switch circuit. This project also introduced the concept of "registering" or aligning multiple printed layers on the same material. The resulting print included a conductive strip that served as part of a folding switch, an LED and coin cell battery that completed the circuit, and a thermochromic image that was printed to decorate the switch. Days 4 and 5 were used to create a screen-printed storyboard that illustrated a narrative developed by the entire class. The inks and concepts learned in the class served as prompts for each frame of the storyboard and served as action points in the story (the final story consisted of four frames which used regular, photochromic, thermochromic, and conductive elements). Table 1 summarizes the structure of our curriculum and the art and science concepts that were covered each day through the activities. The majority of the activities were hands-on except for a longer presentation on electronic.

Day	Activities	STEAM concepts
1	Transfer pre-cut vinyl stencils onto screens, mix photochromic inks, make first print, experiment with UV light.	Screenprinting methods, photochrometry, light perception, visible light spectrum.
2	Introduction of circuits, stencil design in Adobe Fireworks.	Circuits, electronics, digital stencil design.
3	Register (align) and print conductive and thermochromic prints onto foldable material, assemble switch circuit.	Vinyl cutting, registering layered prints, debugging circuits, conductivity of materials.
4	Ideate story using interactive screenprinting elements as prompts; design storyboard stencils in Adobe Fireworks.	Structured brainstorming, storyboarding, collaborative storytelling.
5	Screenprint storyboard; film class narration of story with prints.	Review class concepts, collaborative making.

Table 1. Interactive screenprinting STEAM course curriculum for junior highschool youths.

About the students

18 students (11 female) enrolled in the class, which was one of the most popular in the camp. Of all the students, only two had some prior knowledge of screenprinting and three have previously created basic circuits with wires, but none have worked with interactive inks, stencil making vinyl cutting, or screenprinting in depth.

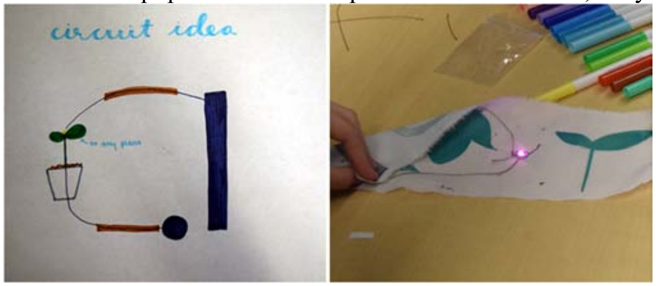

Figure 8. Switch circuit sketched by hand and screenprinted on fabric.

Data analysis and key takeaways

We obtained permission from parents and students to audio record our classes and gather select photos and images. Our classes were organized to embrace informal learning principles of exploratory play, hands-on experimentation, collaborative interactions with other people—principles that are also being increasingly associated with makerspaces in informal learning literature [7, 23]. In informal learning environments, traditional evaluation of science learning (e.g., pre and post tests) may undermine participants' confidence or even deter participation [34]. Similar to prior work that analyzed behavior and dialogue to infer learning patterns [4, 12], our data analysis focused on conversations and behavior during our classes. We audio-recorded and transcribed select aspects of the classes (logistical aspects of the class such as students washing screens were not recorded). We also documented our own in-situ observations at the end of each class, along with audio, photographs, and video recordings. Open coding was applied to relevant portions of the documentation (we did not transcribe or open code parts of the classes where students chatted about irrelevant topics such as their favorite video games or gossip about other students). Open codes were then grouped into themes and we affinity diagramed these to reveal two emergent areas: screenprinting as an integration of art and science; and smart materials as prompts for collaborative making.

Screenprinting as an integration of art and science

Throughout both classes nearly all students commented on how they perceived the class to be a blend of art and science. Certain parts of our curriculum served as particularly salient—and in some cases surprising—prompts for students to engage with STEAM. For instance, during the first day, we expected the students to mix photochromic inks quickly and proceed to screenprinting, since during our initial introductions most of them expressed more interest in the artistic aspects of the class (e.g., designing their own Tshirts). However, the process of adding photochromic pigments engaged the group for over an hour: the students experimented with various paint ratios, tested their results with UV lights or by stepping into the sun, and examined how different background colors of paper affected their color perception. In addition to general comments (e.g., "this is like science"), these experiments also led to many informal discussions about how humans perceive color and why materials change color. We used these conversations as opportunities to explain the concepts of photochromism, color perception, wavelengths of the visible and UV light, the atomic structure of materials, and the process of scientific discovery (scientific method).

Another instance when traditional screenprinting intersected with science and engineering concepts in our class was during the screenprinted circuit assembly. Our class workspace was arranged as an art studio, with a variety of different conductive materials (threads, paint, fabric, glue, etc.) available the same way regular craft materials are laid out during a find arts course. What we observed during days 2 and 3 of the course were children's seamless transitions between work with screenprinting, traditional craft activities, and circuit prototyping. During day 2, we asked the students to sketch out what their print and foldable switch would look like, and this "circuit diagram" guided each group in designing their stencils (Fig. 8). When adding LED's and batteries to their screenprints, the majority of the students informally talked about fundamental circuits concepts with each other, including conductivity, resistance, power, electron transfer, switches, and short circuits. Our set-up, where a variety of digital and fine arts materials were readily available, also led students to experiment with how different conductivities of inks, threads, and copper affected the brightness of their LEDs. Our wrap-up conversations with students asked them to describe what they were doing, and the children characterized their activities as "art and science". This blending of disciplines was further demonstrated by students who used conductive tape or thread to connect extra LEDs to their circuit, and then drew with regular paints or pencils to augment their screenprinted designs.

Screenprinting as a prompt for collaborative making

In our class, the screenprinting process naturally supported collaborative work among the students. On one hand, there

Interactive ink	Brainstorming prompt	Example brainstormed plot point
Any	____ is a ____	Kate is a swan
Photochromic	____ appears the character____	A ghost appears and Kate reaches for the door
Conductive switch	____opens and the character ____	The door opens and Kate steps inside
Thermochromic	____heats up and the character____	The room heats up and Kate regains her superpowers

Table 2. Interactive screenprinting inks as class prompts for collaborative storytelling. Inks were used to illustrate action points in storyboards.

are many steps involved, starting from designing a stencil and vinyl cutting it, to transferring it onto a screen, preparing the ink, printing (this step in particular required students to help each other with the printing press), and washing the screens. On the other hand, since screenprinting can be replicated many times without additional work, every group member can make a copy of the design on any desired material, thereby keeping a customized version of the group project. The last two days of our class supported a collaboration among the entire class of 18 students by using the interactive aspects of our inks as prompts for creative storytelling by the entire group. On day 4, the class was asked to brainstorm four storyline points, which were to be illustrated using each of the screenprinting inks and techniques from class (Table 2). After a collective brainstorming session, students selected their favorite plot line and worked in groups to design storyboards to illustrate each point with the specified inks. When these designs were printed, the students narrated the class story in a short video.

All the students themselves commented on the collaborative nature of our class—e.g., “this class is more interactive [than the other computer-based classes in the summer camp]”, “this is fun”—and many perceived the group activities as a way of “hanging out” with their friends while doing the classwork. In addition, there were many instances when we observed groupwork to be particularly beneficial in supporting creative making practices: students built on each others’ ideas to develop more complex stencils, suggested alternative ways of routing circuits, and, during the last two days of class, worked together to develop a narrative. Moreover, the informal conversations that occurred while working together often resulted in engagement with scientific concepts.

DISCUSSION AND IMPLICATIONS FOR TEI

Our research examined screenprinting as a platform for STEAM engagement with DIY smart material fabrication. To this end, we developed our own ultra low-cost thermochromic, photochromic, and conductive screenprinting inks and ensured they produced consistent responses across a range of substrates. Using these inks in an interactive screenprinting workshop with adult artists revealed future opportunities for material-agnostic displays and custom-made smart materials for different art domains. Moreover, discussions with adult artists inspired us to develop a STEAM summer camp course whereby junior high school students creatively engaged with fine arts, digital design, electronics, and science concepts through screenprinting.

Our work highlights two key advantages of screenprinting when compared to existing projects with responsive inks (e.g., freehand drawing or inkjet printing). First, the versatility and reproducibility of screenprinting across a range of substrates—wood, fabric, cardstock, etc.—presents new opportunities for low-cost and widely accessible smart material fabrication. Second, by being a highly collaborative practice and by integrating techniques from fine arts, material science, and electronics, screenprinting is a novel and powerful platform for STEAM. Below, we elaborate on these two ideas as future directions for applying screenprinting in TEI research.

Screenprinting and DIY fabrication of smart materials

Smart materials present a new and exciting research area for interaction design [e.g., 14, 15, 26, 50, 51]. DIY screenprinting has several unique advantages: it is ultra low-cost, widely accessible in terms of equipment, and does not require specialized domain knowledge. Also, while many smart material fabrication methods are substrate-specific, screenprinting has the additional capability of embedding responsive elements onto most evenly-textured materials. By being widely-accessible and material-agnostic, screenprinting can be used in domains such as dance, photography, sculpture, and information visualization, as our work has shown.

From another perspective, the inherent slowness of thermal actuation and organic color transitions of our inks, as well as the ability to print on most surfaces, are aligned with the recent trend towards calm computing and slow technology [35]. This body of work focuses on slowing down information consumption and presenting users with technologies that are reflective rather than instantly gratifying. Approaches described in our paper can serve as prototyping techniques for the slow technology agenda by embedding deliberately slow interactivity into everyday objects. Moreover, while our research focused on thermochromic, photochromic, and conductive printing, other materials such as biofilms, organic cells, and


Figure 9. Screenprinting as a highly collaborative maker practice: children transferring vinyl stencil onto a frame, exploring photochromic properties of DIY ink with UV light, making a print, and the final photochromic storyboard illustrating a plot point from the class story.

electroluminescent paint could be supported using screenprinting in the future.

Screenprinting as a platform for STEAM

We see screenprinting as parallel to many existing, successful initiatives that incorporate tangible media into art and science curriculums (e.g., textile or paper computing [8, 29]) or integrate computation with more traditional art forms such as glass blowing [21]. However, when compared to these existing methods, screenprinting offers several unique advantages.

First, screenprinting seamlessly combines elements from the fine arts, including one of the oldest forms of printmaking, with modern technologies such as vinyl cutting, and advancements in material science. Another particularly exciting feature of screenprinting is that it naturally supports collaborative making because of the physical aspects of the printing process and the reproducibility of the prints, such that everyone can make and keep a copy of the group project. Collaborative exploration is a tenet of informal learning, whereby participants pursue projects that are of personal interest, learn by doing, and collaboratively exchange ideas [34]. In our summer course, we saw many examples of this—e.g., when children informally discussed concepts of photochromism, thermochromism, conductivity, or human, color perception, during their collaborative troubleshooting of circuits, and class brainstorming and storyboarding.

These aspects of screenprinting—namely the blending of disciplines and the collaborative practice—render it as a particularly powerful platform for STEAM TEI research. Similar to other initiatives that support creative engagement with technology, future work can continue to explore screenprinting in informal learning contexts such as design studios, art-spaces, and makerspaces. Building on the preliminary insights from our studies, future work can more formally evaluate learning outcomes or compare screenprinting with existing STEAM approaches.

Limitations

Our analysis of the prints was carried out using consumer-level equipment—an entry level DSLR camera, regular multimeters and relatively low cost (below $30) sensors. While these lower-cost tools may limit the accuracy of our results, our findings were sufficient for speculating on the potential applications of screenprinting as a DIY fabrication method. While in this paper we focused on analyzing shorter-term performance and consistency, our future and ongoing work investigates longer-term ink stability in order to produce durable interactive systems. For example, some UV and temperature-responsive inks may fade over time, and we noticed a ghosting effect when exposing our prints to extreme heat and sunlight for several weeks. This exposure causes the inks to become less vibrant, but can be reduced by applying a fixative over the top of the prints and/or creating systems that actuate the inks for limited amounts of time. We suspect that these effects may also be reduced by experimenting with different types of pigments (e.g., different commercially available distributors).

CONCLUSION

In this work, we examined screenprinting as a new method for DIY fabrication of smart materials and a platform for STEAM. We first described three types of screenprinting inks we developed for embedding conductive, thermal, and photochromic properties onto most substrates. Our analysis shows that our inks and printing methods produce consistent outcomes across various materials even within a fully manual and basic screenprinting setup. We then studied the opportunities afforded by screenprinting in two STEAM contexts: a workshop with adult artists and a course for junior highschool youths. Our findings demonstrate several unique features of screenprinting: a low barrier to entry for smart material fabrication, a collaborative maker practice, and a creative integration fine arts, material science, and electronic concepts. We suggested that by being widely accessible and substrate-agnostic, screenprinting can be applied to new TEI research in interactive arts, information visualization, and STEAM education. Above all, we hope to have shown that by operating at the intersection of fine arts, material science, and technology, screenprinting bridges diverse disciplines through collaborative making at youth and adult levels.

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