Phosphenes: Crafting Resistive Heaters within Thermoreactive Composites

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THERMOCHROMIC WATERCOLOR
2 SILVER INK RESISTIVE HEATERS

TOUCH DETECTED
ALL HEATERS POWERED

15 SECONDS
LEFT ARMS APPEAR

30 SECONDS
RIGHT ARMS APPEAR

50 SECONDS
ARMS DISAPPEAR, HALO APPEARS

Figure 1. Two joule (resistive) heaters are designed relative to a thermochromic watercolor composition. By constructing resistors in parallel, heat is applied to select regions of the composition but generated at different rates triggering different thermochromic changes over time. The final artifact is a representation of a non-emissive display and "timer" for prayer and reflection.

ABSTRACT

Hybrid practices are emerging that integrate creative materials like paint, clay, and cloth with intangible immaterials like computation, electricity, and heat. This work aims to expand the design potential of immaterial elements by transforming them into manipulatable, observable and intuitive materials. We explore one such immaterial, electric heat, and develop a maker-friendly fabrication pipeline and crafting support tool that allows users to experientially compose resistive heaters that generate heat spatially and temporally. These heaters are then used to couple heat and thermoreactive materials in a class of artifacts we term Thermoreactive Composites (TrCs). In a formal user study, we observe how designing fabrication workflows along dimensions of *composability* and *perceivability* better matches the working styles of material practitioners without domain knowledge of electronics. Through exemplar artifacts, we demonstrate the potential of heat as a creative material and discuss implications for immaterials used within creative practices.

Author Keywords

Craft; materiality; DIY; Creativity support tools; electronics design; thermal design

CCS Concepts

•**Human-centered computing → Interactive systems and tools;** *Systems and tools for interaction design; Interactive systems and tools;* Systems and tools for interaction design;
•**Applied computing → Media arts;**

INTRODUCTION

Abstraction and automation within digital fabrication have given us many powerful levers that compartmentalize specialized knowledge and democratize its use to a larger public. An expanding range of materials is becoming available to novice practitioners, but the knowledge on how to manipulate them is hidden by software and hardware blackboxes, limiting a user's ability to extend, deviate, recover, or reappropriate this knowledge without specialized training and study. How might digital fabrication tools ensure that knowledge which is automated and abstracted maintains itself in the public repertoire while still providing the benefits of speed, accuracy, and efficiency?

Within digital fabrication, immaterials, or elements such as computation, heat, magnetism, or electricity, are the sites of many blackboxes with many readymade components, parts, and systems abstracting away the intricacies of working with the raw element. Although some immaterials represent a physical phenomenon, they share a similar intangibility that complicates the ability to engage in a "material conversation" central to reflective creative practices shared amongst practitioners in a variety of disciplines [3, 34, 18]. Within HCI, computational composites [38] represent one strategy for allowing an immaterial like computation to be used as a material. These composites use a tightly-bound physical proxy to remap behaviors, forms, and structures of computation as physical cues

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(e.g., network traffic materialized via an oscillating wire [19]). While often associated with designing experiential encounters within interaction design [13], more recently this *material turn* in HCI is being used to inform crafting (and material-driven design) practices with immaterials [4, 15].

In this work, we explore the generalizability of computational composites to another immaterial – electric heat. In contrast to work that explores the somatic experiential qualities heat [21], our focus is on building a crafting support tool that foregrounds the behaviors, forms, and structures of electric heat in material-driven practices such as thermoreactive painting (thermochromic pigment), thermoreactive sculpture (thermochromic PLA), and thermoreactive clothing (thermochromic liquid crystal) (Figure 1). Unlike computation, light, or electricity, working with heat is more complex since it reacts to or triggers reactions more slowly making it difficult to control (e.g., hysteresis, power) and perceive (e.g., thermoreceptor fatigue).

Our crafting support tool Phosphenes aids in the making of *Thermoreactive Composites* (TrC), a class of objects composed of a thermoreactive element and a heat-generating element (Figure 2). Phosphenes is oriented around exposing heat and its interactions with other materials as an experiential "conversation" that introduces, adjusts, and satisfies circuit requirements during the act of making. Crafting with resistive heaters is enabled in three ways:

1. Creating an iterative design practice through a maker-friendly fabrication pipeline that captures a composition, facilitates resistive heater design, and debugs and validates fabricated heaters.
2. Communicating the creative constraints between different conductor, power supply, and thermoreactive material combinations while maintaining electrically-valid and power-safe designs.
3. Expanding the malleability, expressivity, and composability of electrical heat through computational design algorithms that allow resistive heaters to activate specific areas of a thermoreactive composition at different times.
4. Exposing a live thermoelectric circuit model using responsive visual annotations, embodied design interactions, and responsive heat visualization (using commodity thermochromic liquid crystal [TLC] sheets).

To evaluate how optimizing the tool along dimensions of composability and perceivability supports material workflows, we administered the Creativity Support Index psychometric survey [7] on users specifically trained in material practices, trained in engineering practices, or trained in both. Comparing respective scores and interview responses, we demonstrate that Phosphenes aligns with material (78.0 ± 7.5) and hybrid (84.3 ± 6.4) practitioners, as opposed to engineering practitioners (65.5 ± 9.5). We synthesize salient themes and discuss the potential for design tools that remap physical stimuli to leverage a wider breadth of human cognitive and motor abilities and its implications for creative development.

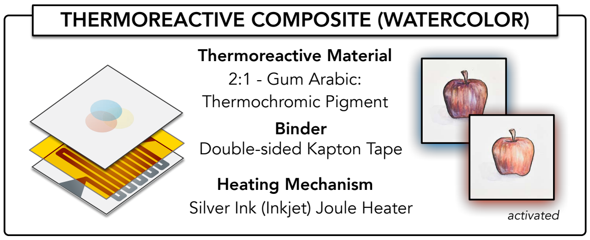

Figure 2. A Thermoreactive Composite. Thermochromic pigments are bound in gum arabic, giving it many of the same qualities as watercolor paints. A purple thermochromic glaze is applied to a chromostable watercolor composition depicting an apple. A silver ink resistive heater is coupled to the composition with Kapton tape; when triggered, it produces a dynamic ripening-apple illustration.

RELATED WORK

Several approaches aim to visualize immaterials (e.g., visual programming, data visualization, material simulation), however the focus on *visual* explanation limits the ability of materials to be used in physical practices; in contrast, our material-centric approach aims to actively transform such immaterials into "an extension of the human body" [28], incorporating more of the body's perceptual and cognitive abilities in the creative sensemaking process. We describe ways diverse communities have developed for working with electric heat.

Heated Practices

Heat has been used to control the activation of a variety of materials within creative practices including metals, glass, and wood. Emerging practices have used thermoelectric heating elements in a variety of form factors including peltier elements [31] and resistive heaters from conductive thread [8, 24], silver ink [14, 40], and gold leaf [23]. Heating elements have been coupled with a variety of thermoreactive materials including gels [22, 29] and thermochromic pigments or liquid crystals [35] suspended in carriers that bind to paper, films, and threads. In multimaterial-layer constructions, the thermal properties of materials have been used as actuation mechanisms [30, 11, 16, 39], as a 3D-forming technique [14, 6], as a sensing technology [2], or as a trigger for secondary effects (e.g. humidity [40]). Jonsson et al. [21] explored the somatic experience of heat and the different aesthetics that can be formed from leveraging the ambiguity of thermoception (e.g., subtleness; subjectivity) or the way heat interacts with materials (e.g., inertia, heat transfer). We add to these expanding practices and contribute a workflow that bolsters explorations with heat and thermoreactive materials through a faster, expressive, and more iterative practice enabled through silver inkjet-printed resistive heaters.

Resistive Heater Design and Fabrication

As a fabrication strategy, many resistive heating applications etch or mill copper plates or use copper wire coils. Resistive heaters have been embedded within existing material practices; Devendorf et al. [8] demonstrated that weaving conductive thread into knitting patterns can also be used to create different heat profiles. Recent advancements in silver ink printing allow for more user-friendly, fast, accurate and effective prototyping techniques for resistive heaters [25]. Within silver ink circuit design, LightTrace [37] utilized the non-negligible resistance introduced by silver-ink traces to regulate current sent to LEDs and computationally adjusts the resistance by altering a trace's width or length. Phosphenes similarly incorporates circuit design patterns to control the power generation rates of resistive heaters but incorporates a *spatial dimension* to constrain heat distribution to user-specified areas and introduces a *temporal dimension* by assembling multiple heaters with different heat generation rates in parallel.

Circuit Design Tools

Circuit design tools have explored increasing the perceivability of electricity in circuits [5]. Toastboard, an instrumented breadboard, allowed users to verify electrical connections and prevent slips [9]. Bifröst [27] provides support for embedded system debugging; in a similar initiative both Bifröst and this work aim to increase the perceivability of electronic components; however, we take a material-centric approach in order to support users without electronics domain-expertise. Our prior work explored design tools that acknowledge the unique resistivity and construction challenges of working with conductive ink, thread, paint, and tape to explore and express LED circuit drawings [26]. Phosphenes similarly supports a variety of thermoreactive materials as well as circuit conductors.

PHOSPHENES TRC DESIGN

In this section, we first review existing resistive heater design workflows and limitations. We then describe the workflow of using Phosphenes, our crafting support tool for Thermoreactive Composites, detail a computational design algorithm for extending the expressivity of resistive heaters, and then annotate perceivability mechanisms for making electric heat behaviors, forms, and structures more salient.

Resistive Heater Design Workflows

Resistive, or joule, heating is a process where electrical current I is converted into heat when electrons collide and transfer energy to conductor atoms [1]. Working with resistive heaters can be decomposed into two major components: (1) regulating an electric current that determines the heater's power, (2) controlling how heat moves through space (diffusion, convection, radiation).

In practice, connecting a resistive heater to a variable power supply and dialing in the input voltage is enough to configure a heater properly. Through trial and error, the heating rate can be adjusted to activate a thermoreactive material. Many commodity hobbyist heaters distribute heat over a small rectangular space; while a limited heat profile, many heaters can be composed side-by-side to heat larger and more varied spaces. This results in many thermoreactive composites having heat trigger a global binary on/off change (e.g., triggering a black thermochromic mask to disappear to reveal a hidden message) rather than leveraging more of heat's interactions with other materials and its respective behaviors and forms.

Constraining heat to a specific area requires custom resistive heaters or custom heat sinks, the latter of which would require expensive metalworking. Resistive heaters on the other hand can be made from conductive thread, copper wire, or silver ink and follow a similar construction pattern: in knowing the amount of power that needs to be generated ($P = IV$), the resistance of the heater can be determined ($R = V^2/P$). There exist a number of ways to cut thread, mill copper, or lay silver ink to satisfy the necessary resistance, but it will dramatically affect how heat is distributed. The most efficient heaters use wire forms in serpentine (or other space-filling curves) patterns to distribute heat evenly. For many wearable applications, the limits of the power supply (e.g., a lithium-ion battery) heavily constrains the power generation rates that are feasible. Controlling more than one heater at a time requires a microcontroller and special current control electrical components (e.g., h-bridge, BJT transistors) that adds significant complexity and a larger footprint (detrimental to many wearable applications).

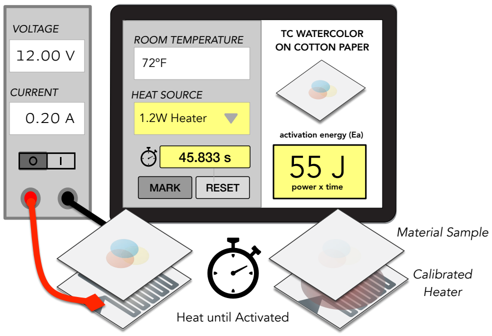

Figure 3. Characterization Routine. A sample of a thermoreactive material is heated using a heater with known power P until a Just Noticeable Difference is detected. The activation energy E_a (from room temperature) can be computed from the product of power and time ($E_a = P\Delta t$).

In this process, the resistive heater, thermoreactive material, and power supply introduce several complex constraints that (1) limit the designs that can be made, (2) restrict the level of engagement with heat to a binary on/off, (3) are imperceivable when working experientially with these components.

Phosphenes Workflow

Phosphenes is a crafting support tool that aids a user in designing a resistive heater specific to a thermoreactive composition. It is composed of a tablet running a paper.js web application, a network connected camera, and an inkjet printer with the AgIC silver ink system. The workflow consists of three stages:

In the *Configuration Stage*, users specify the materials being used in the thermoreactive composite; a library of common conductors, power supplies, and thermoreactive materials allow for quick parameter selection; for parameters like the activation energy of a thermoreactive material E_a, we provide a walkthrough tutorial that describes the process of empirically deriving this value (Figure 3). In the case of a thermoreactive shirt (Figure 4), the parameters are (a) a silver ink conductor [0.4 Ω/sq resistivity, 2W max], (b) 2 AA batteries [3V nominal voltage], and (c) thermochromic pigment on cloth [55J activation energy]. Using the tablet and camera, we record the dimensions of the shirt design and remotely take a picture that forms the backdrop of our digital canvas.

In the *Design Stage* (Figure 4-1), heat can be applied to multiple regions of the design by drawing a polygon on the digital canvas. Through a UI widget, a user can control the heater

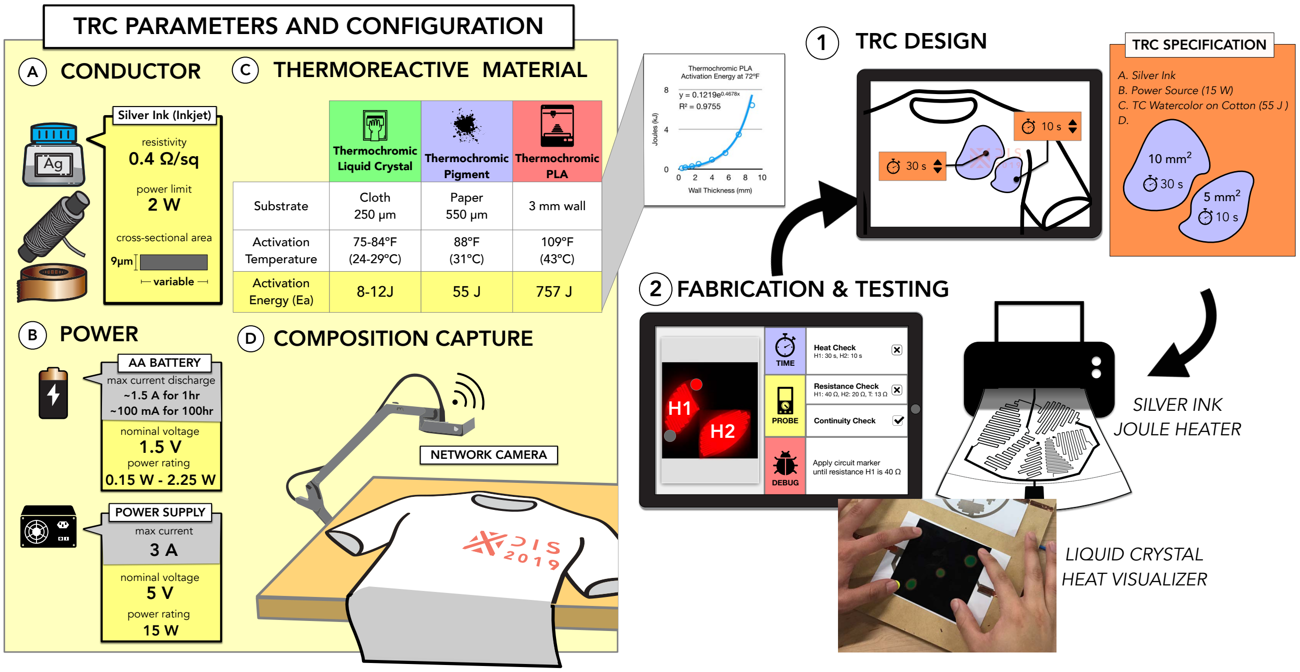

Figure 4. Thermoreactive Composites Fabrication Workflow. Based on parameters derived from components of a Thermoreactive Composite, 1) a digital design tool is used to specify heat regions and desired rise times to output a circuit design, 2) the circuit design is fabricated and validated using highly thermoreactive liquid crystal sheets, providing visual feedback to guide iteration.

pattern, orientation, and the rise time (time to activate thermoreactive material) of each region. Visual annotations on the canvas communicate to the user electrical and thermal properties of the composite and dynamically update as a user adds, adjusts, or removes a heat region or changes a TrC parameter.

Lastly, in the *Fabrication & Testing Stage* (Figure 4-2), circuits are printed and connected to a power supply using paper clips or copper tape. A liquid crystal sheet is used to visualize the circuits heating behavior; the digital design tool issues prompts to help collect feedback ("Region 1 heats up too quickly") into actionable recommendations that can be carried back to the design stage or debugged to resolve printing issues.

We found that a typical iteration for a custom resistive heater design takes less than 10 minutes and is portable to many different thermoreactive composite combinations. In the next section, we describe computational mechanisms and interactions that enable this workflow.

ELECTRIC HEAT COMPOSABILITY

In this section, we describe a computational design algorithm for designing resistive heaters to activate Thermoreactive Composites. Unlike common heater designs, our algorithm introduces a temporal component allowing users to selectively control which areas of a composition activate over time. The core insight is that each resistive heater is a collection of subheaters, connected in parallel to form a current divider circuit. Thus, the ability to control how much current is flowing over selective regions of a circuit allows us to control the activation times of thermoreactive materials. The TrC interactions described in this work are largely driven from the desire to activate a target area of the thermoreactive material within a certain period of time (rise time t) driven by a common power supply with nominal voltage V_S. In order to ensure safe operation, the power of the circuit is capped at the power rating of the conductive material and power supply.

Heating specific regions

Let a heater by modeled as a collection of n resistors R_i connected in parallel. Each resistor is designated a corresponding area A_i to heat up. In this configuration, each resistor i generates power P_i following Kirchhoff's Circuit Laws:

$$P_i = V_S^2/R_i \tag{1}$$

When connected in parallel, resistors share a common input voltage V_S and therefore do not introduce a voltage drop that could affect other resistors. This allows each heater's power to be individually controlled by changing its resistance.

For silver ink (thickness d, and resistivity ρ), resistance can be controlled by either changing the trace length l or width w of silver ink heaters as follows:

$$R = \rho \frac{l}{dw} \tag{2}$$

To fill a specific area A_i with a serpentine pattern ($A = wl$)[1], the width of the trace can be computed as follows:

$$w = \sqrt{\frac{\rho A_i}{dR_i}} \tag{3}$$

Heating at specific times

Since a heater is composed of resistors connected in parallel, a current divider circuit is created (Figure 5 C) allowing

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[1] A conductive material with a small cross-section (i.e., wire) can be used to maximize current flow and localize heat over an area or volume; common patterns include serpentine (e.g., space heaters, radiators) and spiral patterns (e.g., stove heating elements).

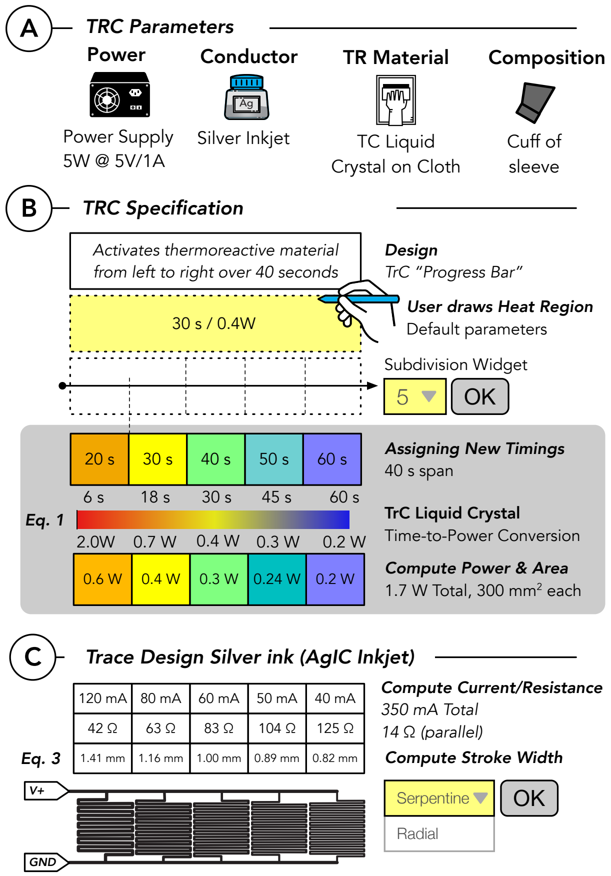

Figure 5. Designing a TrC progress bar. a) The progress bar appears as part of a design on the cuff of a dress shirt. A silver ink joule heater acts as the heating mechanism, activating a silk-screened pattern of thermochromic liquid crystal paint. b) A user draws an initial heat region (per the dimensions of the cuff design), subdivides the region into 5 using a widget, and specifies desired activation times. A computational model updates and computes the power specification; c) circuit design variables are queried for each heat region and a serpentine pattern is generated, specific to silver ink, to achieve the target resistance and power.

us to specify the power generation rate of different areas by adjusting the resistance R_i. The power rate P_i to activate the thermoreactive material at time t is calculated as:

$$P_i = \frac{E_a}{t} \tag{4}$$

where E_a is the activation energy of the thermoreactive material (calculation: Figure 3, table: Figure 4C).

Making a Heater

As an example, we describe the interactions for creating a Thermoreactive Composite "progress bar"(Figure 5). The composite is composed of a silver ink heater inserted into the cuff of a sleeve. The sleeve has a liquid crystal design screen printed onto the cuff. The heater is designed such that when current is supplied to the heater, it will activate the liquid crystal ($E_a = 12J$) pattern from left to right over the course of a minute.

Given the above set of TRC parameters, a user draws a rectangular region (per the dimensions of the cuff design) on the digital canvas. Using a subdivision widget, the user splits this region into 5 subregions in order to assign each region a different rise time. A scale describes the relationships between rise time and power, assigning a color to each combination. Notably, the scale does not allow parameters that would allow unsafe heating rates (2.0 W max, 6 s quickest rise time). The user specifies a target rise time for each region of the progress bar; internally, a circuit model updates the target power, queries respective current draws for each subheater and calculates the trace width to generate a serpentine pattern with the ability to cover the target area. Four different views walkthrough the above interactions: a *thermal view* facilitates drawing heat regions and specifying heat region parameters, a *circuit view* aids with generating and adjusting serpentine patterns, a *temporal view* plays back a simulation of the heater design, and a *print view* presents the final circuit design; the design can then printed, adjusted in Illustrator, or incorporated into more complex circuits.

ELECTRIC HEAT PERCEIVABILITY

While Phosphenes could automatically generate a circuit from user specifications, we instead visually annotate the digital canvas and incorporate embodied interactions to communicate the invisible constraints between different materials and design choices (Figure 6). In our approach, we first consider the human perceptual and cognitive bounds for perceiving and understanding electric heat. From physics education literature, we then derive a thermoelectric modeling analogy to frame our interactions and inform what type of feedback to provide to improve the observability of electric heat and guide the act of designing a heater.

Perceivability of TrCs

Thermoreception. The body has two types of thermoreception sensors that detect temperatures above or below body temperature. Warm receptors are continuously active at constant temperatures above neutral skin temperature $34^{\circ}C(93^{\circ}F)$ [17]. Pain receptors activate at $45^{\circ}C$ $(113^{\circ}F)$ [10], limiting heat judgment to above neutral skin temperature and below the pain threshold. However, thermoreceptors can become desensitized from prolonged exposure to a stimulus requiring a resting phase between temperature probing.

Visual short term memory (VSTM). While triggering a fast TrC interaction can be achieved within a second, the cooling rate is dependent on the difference between the activation temperature and the ambient temperature; for a typical interaction, this results in a 30 second rise and fall interaction. In the creative process, comparing and iterating on a TrC is a typical change-detection task. Due to the limited capacity of VSTM, successfully comparing differences between visual stimuli has been observed to become less effective within a few seconds [32], severely limiting the observability of electric heat interactions with thermoreactive materials.

Mental models. Physics education commonly leverages the water-flow analogy [12], a system of relationships from hydraulics to electricity, in order to aid learners with constructing a mental model of how electrons behave. Alternative analogies include the moving-crowd model where current is represented by masses of objects (e.g., ant, people, cars), moving through passageways (e.g., tunnels, airports, highways). Such models

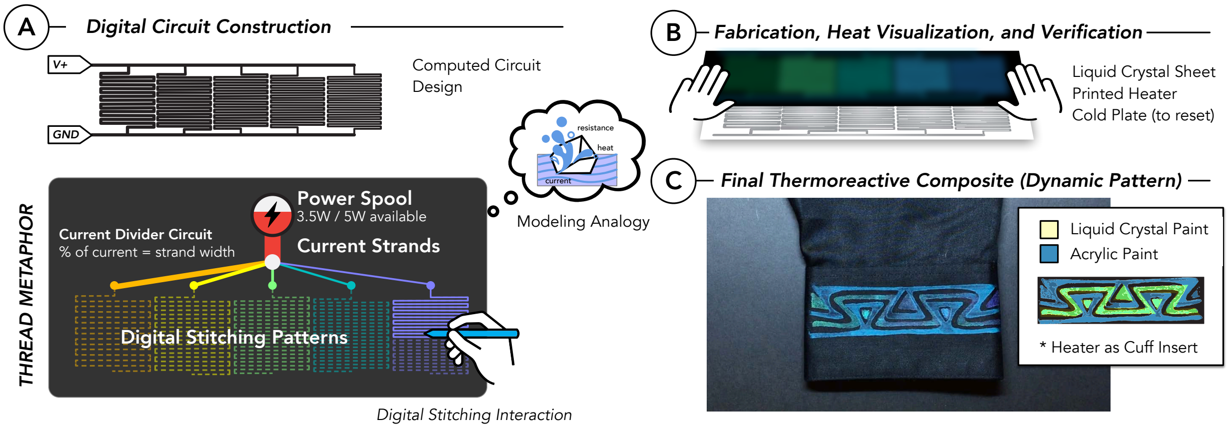

Figure 6. Perceivability mechanisms. A) The generated circuit and underlying circuit model are used to encode an interactive visual representation of circuit state including power consumption, current distribution, and resistance. A digital stitching interaction requires physical effort to produce traces, while a splashing-rock modeling analogy conceptualizes electric heat. B) Liquid crystal sheets with the aid of a cold plate to reset activated materials serve as an iterative heat evaluation technique. C) A TrC sleeve activates from left to right, serving as a wearable progress bar and dynamic texture.

have been shown to lead to better performance on parallel-resistor problems [12], and improve children's understanding of electrical concepts [5], yet carry the tradeoff of needing to be learned on top of the content that is being described [20]. From experience teaching and engaging with silver ink, the inverse relationship between resistance (heat generation rate), trace width, and trace length is a particularly cognitively demanding and confusing aspect of circuit design largely due to circuit properties not being readily perceivable.

Perceivability Mechanisms

Thread Metaphor

To guide the thermal design process, we model the task of creating a heater analogous to tasks in the textile tradition. Our choice for this analogy coincides with the strong similarity of resistive heater design practice (laying out heaters using serpentine patterns) to working with thread in embroidery or cross-stitching practice. This analogy also holds the additional benefit of connoting a craft practice. Using the analogy of power as a thread, we convey the task of apportioning a finite amount of thread to cover regions of a design using patterns to maximize visual density (heat distribution design). When elements are altered on the canvas, our circuit model updates and relays thermal/circuit information using the thread metaphor, depicted in Figure 6A, as follows:

- *Power Spool.* A power supply is represented as a spool of thread, conveying a finite resource (e.g., 5 W of thread). Power consumption is displayed through an animation of drawing thread and using up the power supply coupled with an annotation ("3.5 W remain").
- *Thermogram-colored thread.* In order to convey rise time and the power of the thread, each area is assigned an identifying color (similar to a cross-stitching legend) on the thermogram scale. Red threads heat quickly; blue threads heat slowly.
- *Current Multi-strand Thread* A thread is used to signify edges in a circuit graph where the thickness of the thread is mapped to the current flowing through it. To communicate the mechanics of the current divider pattern, a thread can be divided into thinner threads. In this manner, one thread can subdivide into 5 different threads such that the sum of widths of the child threads equals the width of the parent thread; this reflects Kirchhoff's Current Law, whereby currents entering a node and exiting a node must equal zero. The thread exiting the power node reflects the total current draw of the circuit.
- *Digital Stitching Interaction* (embodied resistance) To cause pause and encourage reflection, our tool does not automatically create the serpentine trace but instead requires users to engage in a physical stitching interaction, moving the hand back and forth over an outline of the trace; the effort from the interaction is proportional to the resistance required to generate the requisite amount of heat. For example, a 6W heater would require 3 passes with the finger, whereas a 0.5 W heater would require 30 passes. Each action pulls the trace along the specified pattern until the end terminal is reached, confirmed with a sound. Occasionally, the trace generation algorithm produces unwanted results which users can correct by "restitching" the trace.

Thermoelectric modeling analogy

Conduction and other thermodynamic principles are absent from common electrical modeling analogies. To better concretize thermoelectric concepts, we extended the water-flow analogy to convey resistive losses via heat or light: rocks in the electron river are used to represent resistance; water striking the rocks represents energy being released (Figure 6A). Thermoreactive materials then function as nets that capture energy at different rates, e.g., a TLC sheet changes color when it has captured more than 50J of energy.

Electric heat visualization

Initially, we used an infrared camera to extract a meaningful heat visualization, however, such cameras were limited by resolution, frequent calibration, and a dependence on uniform infrared reflection. Large emissivity variations in materials produce inaccurate readings – this was the case with low emissivity silver ink. Instead, we used a passive visualization strategy with thermochromic liquid crystal (TLC) sheets with effective RGB color changes over $10^{\circ}F$ ($5^{\circ}C$). By placing the sheet over the heating element, a user can visualize heat distribution and heat flux (Figure 6B). While a slight gap between the heater and the sheet can affect heat transfer, mechanical housing (e.g., picture frame) or a magnetic substrate can be used to apply uniform pressure and reduce convection. To aid with temporal perception and iteration, a cold plate was introduced to "reset" a TrC back to steady state. The cold plate is composed of a 92W peltier element (TEC1-12706) bound with thermal paste to a steel bench block (hot side) and aluminum sheet (cold side). The cold plate achieved temperatures between 50–60°F (10–15°C), bringing fall times to 2 s.

DESIGN EVALUATION

To assess how Phosphenes supports crafting resistive heaters and working with heat, we invited participants from material practice and engineering backgrounds to attend a 1-hour workshop. This workshop was specifically designed to build familiarity with the unique challenges and opportunities of working with thermoreactive composites and to contrast the experiences of these different practitioners. In a pilot study, participants were asked to design a thermoreactive watercolor and resistive heater. A challenge of this setup was navigating the bias in familiarity: participants focused primarily on either their heater or their watercolor, restricting their exposure to unique TrC design challenges. We found that focusing the task on designing a heater to trigger a readymade composition allowed for many of the unique TrC concerns to surface, i.e., where to spatially generate heat and how to trigger a composition to have a meaningful composition.

Protocol. In our final workshop, we tasked participants with designing a heater that when triggered would cause 3 areas of a readymade thermoreactive watercolor (12 thermoreactive circles arranged in a 3x4 grid) to disappear. Participants were also interviewed beforehand on perceptions of electricity and heat as creative elements and engaged in a think-aloud protocol when viewing a range of thermoreactive materials, different thermoreactive composite combinations and exemplars, and in the heater design and fabrication task. Lastly, we conducted a post-study semi-structured interview probing on future creative trajectories, discoveries, and frictions.

Participants. Participants were recruited from departmental mailing lists in Design, Engineering, and New Media. A total of 19 participants (10 female, 9 male, avg. age 22 ± 4) took part in the study and were grouped based on survey responses querying familiarity with creative mediums, electronics tools, techniques, and theory as follows:

- Engineering (**E**) - 7 participants had extensive experience with circuit design, electrical concepts (e.g., Kirchhoffs' circuit laws), and heat transfer concepts.
- Material (**M**) - 7 participants were well-versed in material practices ranging from painting, quilting, and metalworking.
- Hybrid (**X**) - 5 participants possessed extensive experience in both engineering and material practices.

Measures

Creative Potential of TrCs. Unlike productivity support tools, creativity support tools are difficult to assess due to a large number of design variables and confounds without obvious measures to quantify (e.g., performance, time and error) [36]. For this reason, we administered the creativity support index [7], a psychometric survey grounded in creativity support tools literature which measures how well a tool "assists a user engaged in creative work". The index derives a possible 100 point score composed from assessments of 6 creative factors (Figure 7A). The score for each factor is determined in two parts: (1) a *factor count* independent of the task used to reflect a user group's preference for each creative factor (5 point max[2], Figure 7B), (2) a *factor score* from two 10-point Likert scale questions (20 point max, Figure 7C). The factor count is used to weight the factor score; the resulting values are combined for a holistic CSI score. The index was used to evaluate the creative act of designing resistive heaters for use in thermoreactive composites; although the workshop task was scoped to thermoreactive watercolors, participants were asked to consider the tool's support for using the same workflow for other thermoreactive composite combinations.

Perceiveability of TrCs. Participants filled a post-study questionnaire with Likert scale questions querying the perceivability and comfort of working with circuit concepts like resistance, current, power, and Kirchhoff's circuit laws as well as thermal concepts like conduction. In addition, we transcribed think-aloud audio, logged design tool interactions, and kept an inventory of heater prototypes.

QUALITATIVE RESULTS

All participants successfully designed a resistive heater with at least three resistors with different power requirements; all but one heater was functional; the defective heater was diagnosed during the study by the participant and researcher and resolved to be a printing error. Despite using the same thermoreactive composition, designs ranged from 3-6 resistors with motifs of form-giving heating elements (e.g., figurative rivers), symbolic relationships with the artwork (e.g., making cool-colored circles fade away), or pushing the limits of the fabrication and materials (e.g. maximum temporal difference; consuming all available power). We first report Likert ratings, CSI results, and then present themes that were observed from the think-aloud and semi-structured interviews.

Perceivability Ratings. On average, participants reported on a Likert scale from 0 to 10: comfort with the design and fabrication process (8.6 ± 1.1), comfort with working with joule heaters (8.4 ± 1.3), and an understanding of the electricity and thermal mechanics (9.0 ± 1.1). The process and electronics were viewed as approachable (9.1 ± 1.2).

CSI Results. Participant groups notably differed by the value placed on Exploration by hybrid practitioners (count 4.8X versus 3.9E and 3.7M) versus the value placed on Enjoyment by material practitioners (count 3.1M, versus 2.1E and 2.8X), and Results Worth Effort by engineering practitioners (count 3.7E versus 2.7M, 3.0X).

The CSI final adjusted score (Figure 7D) for each group breaks down as follows: engineering practitioners (65.5 ± 9.5), creative material practitioners (78.2 ± 7.4) and hybrid practitioners (84.3 ± 6.4). As a baseline, Cherry et al. reported Google

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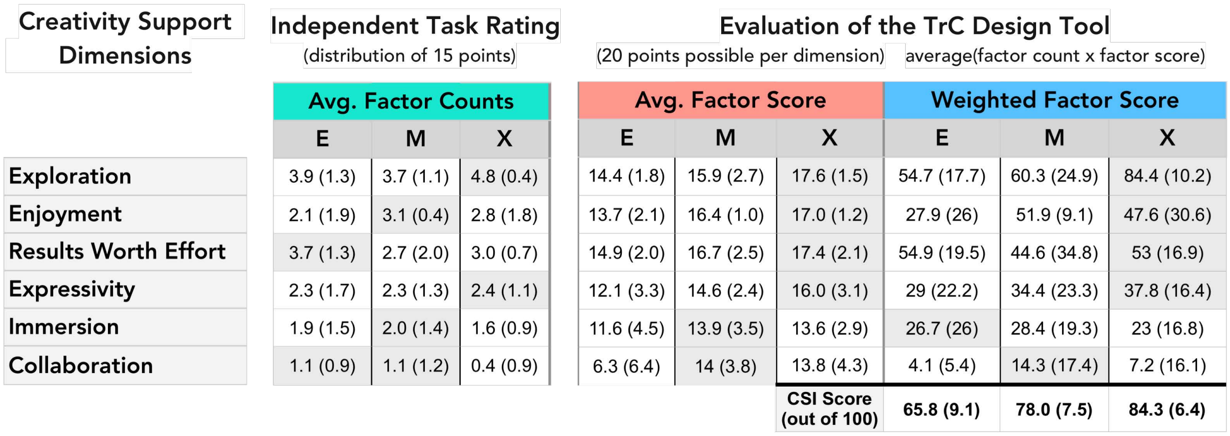
[2] Each creative factor is compared against the 5 other factors; a factor score represents the number of times a factor is valued over others; only 15 pts are distributed amongst the 6 factors representing the 15 possible combinations of factor pairs.



Creativity Support Dimensions	Independent Task Rating (distribution of 15 points)			Evaluation of the TrC Design Tool (20 points possible per dimension)			average(factor count x factor score)		
	Avg. Factor Counts			Avg. Factor Score			Weighted Factor Score		
	E	M	X	E	M	X	E	M	X
Exploration	3.9 (1.3)	3.7 (1.1)	4.8 (0.4)	14.4 (1.8)	15.9 (2.7)	17.6 (1.5)	54.7 (17.7)	60.3 (24.9)	84.4 (10.2)
Enjoyment	2.1 (1.9)	3.1 (0.4)	2.8 (1.8)	13.7 (2.1)	16.4 (1.0)	17.0 (1.2)	27.9 (26)	51.9 (9.1)	47.6 (30.6)
Results Worth Effort	3.7 (1.3)	2.7 (2.0)	3.0 (0.7)	14.9 (2.0)	16.7 (2.5)	17.4 (2.1)	54.9 (19.5)	44.6 (34.8)	53 (16.9)
Expressivity	2.3 (1.7)	2.3 (1.3)	2.4 (1.1)	12.1 (3.3)	14.6 (2.4)	16.0 (3.1)	29 (22.2)	34.4 (23.3)	37.8 (16.4)
Immersion	1.9 (1.5)	2.0 (1.4)	1.6 (0.9)	11.6 (4.5)	13.9 (3.5)	13.6 (2.9)	26.7 (26)	28.4 (19.3)	23 (16.8)
Collaboration	1.1 (0.9)	1.1 (1.2)	0.4 (0.9)	6.3 (6.4)	14 (3.8)	13.8 (4.3)	4.1 (5.4)	14.3 (17.4)	7.2 (16.1)
						CSI Score (out of 100)	65.8 (9.1)	78.0 (7.5)	84.3 (6.4)

Figure 7. The Creativity Support Index rating averages and standard deviations across six factors and three user groups. A task rating reflects a user group's preferences and is used to weigh the final score. Darker regions represent maxima across groups.

Docs for a collaborative creative writing task with a CSI score of 87.73 (SD=11.30). These scores suggest a stronger affinity for the tool by hybrid and material practitioners and that an epistemological difference exists that can be supported by creativity support tools. Out of important factors, expressiveness was least supported for engineering practitioner (12.1/20.0), many citing a desire to have more control over parameters.

Familiarity of materials and process

The CSI factor score revealed the presence of an epistemological difference between engineering and material practices. Between the two practices, participants distinguished the focus on specification-based problem-solving in electronics as opposed to the open-ended nature of creative tasks. A common friction was adapting designs to fit the ecology of materials and components available and how widely they differ within their class (e.g., choosing motors, microcontrollers). Despite the tool automatically resolving current, voltage, and resistance values to fit a power specification, the tool did not provide an avenue for engaging with circuit equations, symbol manipulation or analysis. For engineering practitioners, the inability to engage with circuits in mismatched their creative process. This might additionally explain why engineering participants rated a lower expressiveness score since such familiar elements drive their workflows for circuit design. The parallel circuit construction strategy was viewed as a major comfort and simplification:

> **X2** I feel so much more comfortable knowing [parallel construction] as a design parameter.

> **X5** I think with voltage and voltage drops. The interface changed this to thinking in terms of power rates and rise times.

In contrast, for material practitioners, the familiarity of material form factors such as paper and ink reinforced and matched their creative process. Electronics were viewed as being more brittle, susceptible to dysfunction, and lacking the kind of freedom of combination (or composability) as creative materials.

> **X3** These are very familiar kind of tools: you use paints, things that look like pieces of paper, you use colors and those visual signals ... it's a lot more approachable than electronics in the other sense.

Hybrid practitioners described their process as *sketching with hardware*, finding elements that spur their curiosity, then designing and engineering its function. Many relished the problem-solving component common in both practices, and described methods of probing and examining the invisible quality of electronics:

> **X5** It's not easy to see what is happening. I work backward, first looking at readouts from pins. I connect wires to probe and see if I can get the value I expect and keep forming hypotheses until I'm sure I understand what is happening.

The familiarity of both practices by hybrid practitioners acted similar to a buffer solution, resisting and stabilizing adverse effects of defamiliarization, suggesting opportunities to develop curriculum that incorporates multiple disciplinary methods as a means of creating more resilient creative practices that can withstand exposure to unfamiliar elements.

Aesthetics of Electronics Design Tools

Aesthetics played a large role in perceptions of approachability, audience, and use. Participants found an affinity to the constructionist elements integrated into the tool: the familiarity of icons like the power symbol, animations like the draining power supply, the focus on color, the friendly rounded-edges of the serpentine patterns, and a nostalgic association and kinship with the Microsoft Paint program. Although all participants perceived a clear benefit over current circuit design tools, many strongly associated the interface as geared towards children. This suggests an opportunity exists to consolidate how constructionist elements are presented to reflect the aesthetics of professionalism (e.g., encoding variables as visual patterns versus color).

Contract of the Digital Hand

A common friction and surprise occurred when participants engaged in sketching interactions. One interaction, sketching a path to specify a heat region, caused pause, reflection, and unhappiness when the path retained its imperfect, hand-drawn look. In contrast, the digital stitching interaction rendered a smooth, regular, and even space-filling curve as the participant moved their finger back and forth. Participants expected that their hand-drawn strokes would be transformed into "perfect", aligned geometries. Such computer-mediated elements were seen to form a contract with the user, where both computer and user shared responsibility for the outcome:

> **E1** If that were automated and [a badly drawn path] happened, it would be annoying. It would think the system should have known better. I would have blamed it on the system, but having drawn it I feel like I take some responsibility in what actually happened.

This suggests that opportunities exist to design onboarding practices that scaffold and balance responsibility between human and machine to slowly instill reward and confidence.

Role of the Digitial Stitching Interaction

In order to generate the serpentine pattern, users had to carry out a digital stitching action with a physical gesture; the serpentine path would only be generated once the amount of effort matched the resistance (and power rate) of the region in order to communicate how resistance reduced the heat generation rate of respective heaters. This stitching interaction was met with a bimodal response. Foreseeing the need to design a joule heater quickly, engineering and hybrid participants viewed the interaction as fun but frustrating and desired the ability to access this interaction as a configurable setting, scoring its value as a 2.9(1.9)[E] and 3.2(0.8)[X] on a 5-pt Likert. However, when the serpentine algorithm produced an undesirable result, participants viewed it as a troubleshooting technique that communicated the limitations and process of the serpentine algorithm.

> **E4** It feels like a troubleshooting technique; doing that motion makes sure that [the circuit] is okay. For me, it's another level of check that makes you aware.

Material practitioners scored and perceived the digital stitching interaction *quite differently* 4.9(0.4)[M]. Initially viewing the act of making the serpentine pattern as complicated, they found the act of creating the serpentine pattern as engaging, joyful, and instilling agency:

> **X5** It was fun and felt like you were making it like you had a role in the work.

> **X3** It made me feel like I was building the circuit myself; it gave me an understanding. I could have done it the other way [automatic generation], but creating the [traces] myself made me know what's going on inside.

Power as a creative material

Before being introduced to the tool, participants revealed different mental models of heat: one participant likened heat as a flow, taking time to move through materials; others described heat in terms of the everyday control mechanisms, e.g., controlling strength with a stove dial. As a creative material, many considered heat a byproduct: When I work with heat, it's about minimizing heat. Heat is not a desirable property (**E4**). Electronics behind heat were perceived as complex; however, one participant, having previously deconstructed a hot glue gun, noted:

> **X3** I thought [the glue gun] would be very complicated, or anything that works with heat. I took it apart and found that the only thing that was producing the heat was these two metal plates ... It's actually just a resistor in there! It was rather surprising that it was so simple.

When participants were presented with the water-flow modeling analogy, reactions were mixed: some had never heard the water-flow analogy, yet were surprised at how easy it was to pick up or how much it aligned with their mental model. For engineering participants, the water analogy misaligned with their way of thinking, having already constructed a model based on formal definitions. The extension of the thermoelectric concepts, i.e., electron water colliding with resistive rocks caught by thermoreactive nets, was welcomed by all and viewed as a natural extension and "filling a gap".

The thread metaphor was viewed positively by all participants. Many described annotations of current and resistance in the cognitive background; their main focus was working with watts and distributing power to heat spaces. A major conceptual discovery that occurred with all participants was understanding power as a finite quantity.

> **X4** I quickly realized from how the power source was draining that there are only so many watts available.

Compared to probing circuits with a multimeter, evaluating the heater with the liquid crystal sheet was preferred by all groups. As a visually engaging medium, the liquid crystal encouraged users to think about the mechanics of heat.

> **E4** It is so cool to watch the liquid crystal change color. It makes me think about how the heat flows through the paper and heat transfer in general.

Participants noted a shift in how they conceptualized electricity and their relationship towards it.

> **X4** It changes your relationship to electricity completely. I think it shows you a different aspect of electricity; where electricity doesn't just hurt you, shock you, is just used to power your electronic device, but can be used creatively... this process makes it more intimate.

The perceivability of electric heat and the material ecology around TrCs drove participant's perceptions about electricity:

> **X5** The [TLC sheet] fixes electronics for me. It is a different, more fun, way of seeing electricity happen.

> **M4** I feel electricity as more friendly, and I would enjoy doing this at home.

> **X3** I thought that electronics were their own system. They are daunting since you don't know anything about them. They are closed-off. I can't go into that and touch things and find out how to work with them. Now, I can put [thermoreactive materials] on [heaters], and they will respond. I can do different tests with it. It feels a lot more accessible on the hardware side. I don't need to go into the code, decompose the circuit, or connect new wires. It becomes a lot more visual and interactive, and in the process, I actually learn what is going on within the [resistors].

DISCUSSION

In this work, the concept of computational composites was applied to electric heat in the form of Thermoreactive Compos-

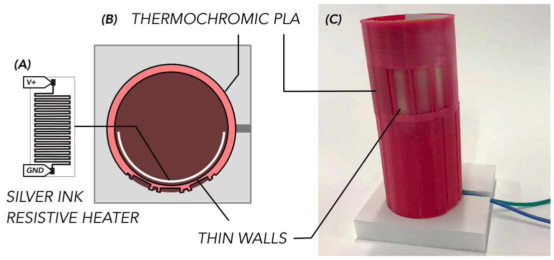


Figure 8. A Thermoreactive Print. (a) A silver ink resistive heater is placed inside a thermoreactive 3D print, (b) the thickness of the 3D-printed walls is used to modulate the mass in contact with the uniform heat source in the interior, (c) the thinner walls activate first, creating a windowing effect.

ites; however, due to the complex and invisible constraints of the conductor, thermoreactive materials, and power supplies, these composites need to be carefully configured to allow heat to "be expressed as a material".

Configuring Immaterial Composites

Phosphenes allows designers to develop resistive heaters specific to the thermoreactive materials and power supplies at hand. In the act of crafting the resistive heaters, the tool communicated creative constraints, updating visual cues that (1) communicate how different heaters change the power requirements of the circuit and whether the configured power supply and conductor will be able to safely satisfy them, and (2) building in a digital making interaction that requires physical effort from the user to complete the circuit design.

Unlike the responsiveness of computational composites, the relationship between heat and electricity was less visible in color-changing textiles, prints, or paintings. We leveraged a thermoelectric circuit model to represent this relationship and leverage simulation to render how heat would activate different materials for quicker iteration. Using the TLC sheets, heat was remapped from a haptic experience to a visual experience which reinforced many participant's mental model of electric heat but also altered their conceptions of heat as a creative material. We did not end up using the body's natural thermoception since many different Thermoreactive Composite combinations had a temperature differential that would be difficult to detect; we see opportunities to explore other modalities like activating scent as a way to engage more of the body in sensemaking or develop a haptic device that senses these minute changes in temperature and renders them to match the psychophysics of the body.

Participants found that many of tool's elements receded into the cognitive background as they actively engaged in wayfaring behaviors, corresponding with the morphogenetic model of making [18]. Specifically, we observed designs evolve as participants interacted with the tool, especially influenced by the diminishing "power spool" that would respond to changes in the design or from the quality of heat distribution when using the TLC sheets.

Alternative Sites for Crafting Heat

Although the relationship with electric heat was conveyed and approachable, the creative potential for heat was only slightly breached. Phospones lowered the barrier and expense of visualizing heat interactions using TLC sheets and the design time for fabricating a custom heater. Figure 8 shows one Thermoreactive Composite (silver ink, thermochromic PLA) that reached the creative bounds of the resistive heaters. With a 2-3W power limit, silver ink could only trigger changes in particularly thin walls of thermochromic PLA in the < 1-minute range. However, changing the thickness of the walls was another way in which heat could be controlled and mediated since more mass requires more energy to activate. In this way, the thermoreactive material becomes the site in which heat is crafted. Mass is just one of many design variables that heat sink design is well suited to capture. While heat sinks are traditionally made from metal, it would be useful to also capture and incorporate these design practices into TrCs.

Extending Heat as a Material

Although systems with peltier elements have introduced cooling elements [31], controlling how thermoreactives react when cooling remains an unexplored creative area. A wider range of thermal materials could enable new creative dimensions. Thermal insulators like silicone could be used to edit, erase, and refine joule heater elements. Other conductive materials may include mechanically-attached heat sinks for selective heat transfer or the use of thermal compounds (pastes and adhesives) to smooth out heating artifacts. Cross-flow blowers could introduce a convection element and push cool or warm air through air-pipes in 3D objects([33]) to influence thermoreactive material activation. Silver ink is limited in both its power rating and archivability. While copper-plated PCBs serve as an alternative, other physical, creative practices like wire bending can be introduced to create stable three-dimensional heating elements and support broader working ranges. Our techniques worked well for material activations under the human thermal perception threshold, but working with hotter materials tangibly remains an open question that creative practices like glass blowing and welding may inform.

CONCLUSION

We demonstrated a crafting support tool for designing resistive heaters in Thermoreactive Composites. Through the computational design of heater geometries and a thermoelectric model, our system exposed the ability to craft resistive heaters that could distribute heat spatially and temporally while accurately activating a range of thermoreactive materials. In a formal user study, we validated that our design and fabrication workflow facilitates an iterative design cycle that conveys both electrical design and thermal design concepts and renews role of heat as a creative material. Through the Creativity Support Index, the study revealed a greater affinity for material-centric design practices and the potential for *composability* and *perceivability* to act as driving design variables to support a wider range of users to participate in digital fabrication.

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REFERENCES

[1] 2018. The Joule Heating Effect. (2018). `https://www.comsol.com/multiphysics/the-joule-heating-effect`

[2] Yomna Abdelrahman, Alireza Sahami Shirazi, Niels Henze, and Albrecht Schmidt. 2015. Investigation of Material Properties for Thermal Imaging-Based Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 15–18. DOI: `http://dx.doi.org/10.1145/2702123.2702290`

[3] Art21. 2017. Sacred Grounds. (Oct. 2017). `https://art21.org/playlist/sacred-grounds/`

[4] Bahareh Barati, Elisa Giaccardi, and Elvin Karana. 2018. The Making of Performativity in Designing [with] Smart Material Composites. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, 5:1–5:11. DOI: `http://dx.doi.org/10.1145/3173574.3173579`

[5] Elham Beheshti, David Kim, Gabrielle Ecanow, and Michael S. Horn. 2017. Looking Inside the Wires: Understanding Museum Visitor Learning with an Augmented Circuit Exhibit. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 1583–1594. DOI: `http://dx.doi.org/10.1145/3025453.3025479`

[6] Jianzhe Gu Tingyu Cheng Xiang 'Anthony' Chen Xiaoxiao Zhang Wei Zhao Youngwook Do Shigeo Takahashi Hsiang-Yun Wu Teng Zhang Lining Yao Byoungkwon An, Ye Tao. 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA. `http://morphingmatter.cs.cmu.edu/thermorph-jianzhe/`

[7] Erin Cherry and Celine Latulipe. 2014. Quantifying the Creativity Support of Digital Tools through the Creativity Support Index. *ACM Transactions on Computer-Human Interaction* 21, 4 (June 2014), 1–25. DOI: `http://dx.doi.org/10.1145/2617588`

[8] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I Don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 6028–6039. DOI: `http://dx.doi.org/10.1145/2858036.2858192`

[9] Daniel Drew, Julie L. Newcomb, William McGrath, Filip Maksimovic, David Mellis, and Björn Hartmann. 2016. The Toastboard: Ubiquitous Instrumentation and Automated Checking of Breadboarded Circuits. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 677–686. DOI: `http://dx.doi.org/10.1145/2984511.2984566`

[10] Eli Eliav and Richard H Gracely. 2008. Chapter 3 - Measuring and assessing pain. In *Orofacial Pain and Headache*, Yair Sharav and Rafael Benoliel (Eds.). Mosby, Edinburgh, 45 – 56. DOI: `http://dx.doi.org/https://doi.org/10.1016/B978-0-7234-3412-2.10003-3`

[11] Samuel M. Felton, Michael T. Tolley, Cagdas D. Onal, Daniela Rus, and Robert J. Wood. 2013. Robot self-assembly by folding: A printed inchworm robot. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*. IEEE, 277–282.

[12] Dedre Gentner and Donald R. Gentner. 1982. *Flowing Waters or Teeming Crowds: Mental Models of Electricity.* Technical Report. DTIC Document. `http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA115300`

[13] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. ACM Press, 2447–2456. DOI: `http://dx.doi.org/10.1145/2702123.2702337`

[14] Daniel Groeger, Elena Chong Loo, and JÃijrgen Steimle. 2016. HotFlex: Post-print Customization of 3D Prints Using Embedded State Change. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 420–432. DOI: `http://dx.doi.org/10.1145/2858036.2858191`

[15] Shad Gross, Jeffrey Bardzell, and Shaowen Bardzell. 2014. Structures, Forms, and Stuff: The Materiality and Medium of Interaction. *Personal Ubiquitous Comput.* 18, 3 (March 2014), 637–649. DOI: `http://dx.doi.org/10.1007/s00779-013-0689-4`

[16] Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. 2015. uniMorph: Fabricating Thin Film Composites for Shape-Changing Interfaces. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 233–242. DOI: `http://dx.doi.org/10.1145/2807442.2807472`

[17] Herbert Hensel. 1973. Cutaneous Thermoreceptors. In *Somatosensory System*, Ainsley Iggo (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 79–110. DOI: `http://dx.doi.org/10.1007/978-3-642-65438-1_4`

[18] Tim Ingold. 2013. *Making: Anthropology, archaeology, art and architecture*. Routledge.

[19] Natalie Jeremijenko. 1995. Live Wire (Dangling String). (1995). `LiveWire,http://www.nyu.edu/projects/xdesign/mainmenu/archive_livewire.html`

[20] Samuel Johsua and Jean-Jacques Dupin. 1993. Using "Modelling Analogies" to Teach Basic Electricity: A Critical Analysis. In *Learning Electricity and Electronics with Advanced Educational Technology*, Michel Caillot (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 39–55.

[21] Martin Jonsson, Anna Ståhl, Johanna Mercurio, Anna Karlsson, Naveen Ramani, and Kristina Höök. 2016. The aesthetics of heat: guiding awareness with thermal stimuli. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 109–117.

[22] Hsin-Liu (Cindy) Kao, Miren Bamforth, David Kim, and Chris Schmandt. 2018. Skinmorph: Texture-tunable On-skin Interface Through Thin, Programmable Gel. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers (ISWC '18)*. ACM, New York, NY, USA, 196–203. DOI: `http://dx.doi.org/10.1145/3267242.3267262`

[23] Hsin-Liu (Cindy) Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016a. DuoSkin: Rapidly Prototyping On-skin User Interfaces Using Skin-friendly Materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers (ISWC '16)*. ACM, New York, NY, USA, 16–23. DOI: `http://dx.doi.org/10.1145/2971763.2971777`

[24] Hsin-Liu (Cindy) Kao, Manisha Mohan, Chris Schmandt, Joseph A. Paradiso, and Katia Vega. 2016b. ChromoSkin: Towards Interactive Cosmetics Using Thermochromic Pigments. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 3703–3706. DOI: `http://dx.doi.org/10.1145/2851581.2890270`

[25] Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant Inkjet Circuits: Lab-based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '13)*. ACM, New York, NY, USA, 363–372. DOI: `http://dx.doi.org/10.1145/2493432.2493486`

[26] Joanne Lo, Cesar Torres, Isabel Yang, Jasper O'Leary, Danny Kaufman, Wilmot Li, Mira Dontcheva, and Eric Paulos. 2016. Aesthetic Electronics: Designing, Sketching, and Fabricating Circuits Through Digital Exploration. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 665–676. DOI: `http://dx.doi.org/10.1145/2984511.2984579`

[27] Will McGrath, Daniel Drew, Jeremy Warner, Majeed Kazemitabaar, Mitchell Karchemsky, David Mellis, and Björn Hartmann. 2017. Bifröst: Visualizing and Checking Behavior of Embedded Systems Across Hardware and Software. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 299–310. DOI: `http://dx.doi.org/10.1145/3126594.3126658`

[28] Marshall McLuhan. 1964. Understanding media. *The Extensions of Man. New York* (1964).

[29] Viktor Miruchna, Robert Walter, David Lindlbauer, Maren Lehmann, Regine von Klitzing, and Jörg Müller. 2015. GelTouch: Localized Tactile Feedback Through Thin, Programmable Gel. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 3–10. DOI: `http://dx.doi.org/10.1145/2807442.2807487`

[30] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 223–232. DOI: `http://dx.doi.org/10.1145/2807442.2807494`

[31] Roshan Lalintha Peiris and Suranga Nanayakkara. 2014. PaperPixels: A Toolkit to Create Paper-based Displays. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14)*. ACM, New York, NY, USA, 498–504. DOI: `http://dx.doi.org/10.1145/2686612.2686691`

[32] W. A. Phillips. 1974. On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics* 16, 2 (01 Mar 1974), 283–290. DOI: `http://dx.doi.org/10.3758/BF03203943`

[33] Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A Series of Tubes: Adding Interactivity to 3D Prints Using Internal Pipes. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 3–12. DOI: `http://dx.doi.org/10.1145/2642918.2647374`

[34] Donald Schon. 1983. The reflective practitioner. (1983).

[35] Midori Shibutani and Akira Wakita. 2006. Fabcell: Fabric Element. In *ACM SIGGRAPH 2006 Sketches (SIGGRAPH '06)*. ACM, New York, NY, USA. DOI: `http://dx.doi.org/10.1145/1179849.1179990`

[36] Ben Shneiderman. 2007. Creativity Support Tools: Accelerating Discovery and Innovation. *Commun. ACM* 50, 12 (Dec. 2007), 20–32. DOI: `http://dx.doi.org/10.1145/1323688.1323689`

[37] Tung D. Ta, Fuminori Okuya, and Yoshihiro Kawahara. 2017. LightTrace: Auto-router for Designing LED Based Applications with Conductive Inkjet Printing. In *Proceedings of the 1st Annual ACM Symposium on Computational Fabrication (SCF '17)*. ACM, New York, NY, USA, Article 3, 10 pages. DOI: `http://dx.doi.org/10.1145/3083157.3083160`

[38] Anna Vallgårda and Johan Redström. 2007. Computational Composites. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 513–522. DOI: `http://dx.doi.org/10.1145/1240624.1240706`

[39] Guanyun Wang, Youngwook Do, Tingyu Cheng, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. 2018. Demonstrating Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article D105, 4 pages. DOI: `http://dx.doi.org/10.1145/3170427.3186531`

[40] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. bioLogic: Natto Cells As Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1–10. DOI: `http://dx.doi.org/10.1145/2702123.2702611`