Towards Designing for Everyday Thermal Experiences

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ABSTRACT

This pictorial helps expand thermal interaction design toward more situated experiences in everyday life. First, we map existing thermal display applications and techniques, identifying an under-explored niche of thermal displays that rapidly change temperature (fast-switching) without touching the body (non-contact). Second, we explore this niche with scenarios showing everyday interaction possibilities, including Candlelit Dinner, Calming Compact Mirror, Social Foot Bath, Fried Ice Cream, Thermal Painting, and VR Diwali, among others. Finally, our discussion contributes design directions regarding heat as a design material, personalized thermal comfort in shared settings, cultural and emotional associations with heat in everyday contexts, and facial thermal interactions. Overall, this pictorial contributes to designing for everyday thermal experiences.

Author keywords

Thermal display; thermal interaction; thermal feedback; embodied interaction; haptic interaction; somaesthetics.

CSS concepts

- Human-centered computing~Interaction design

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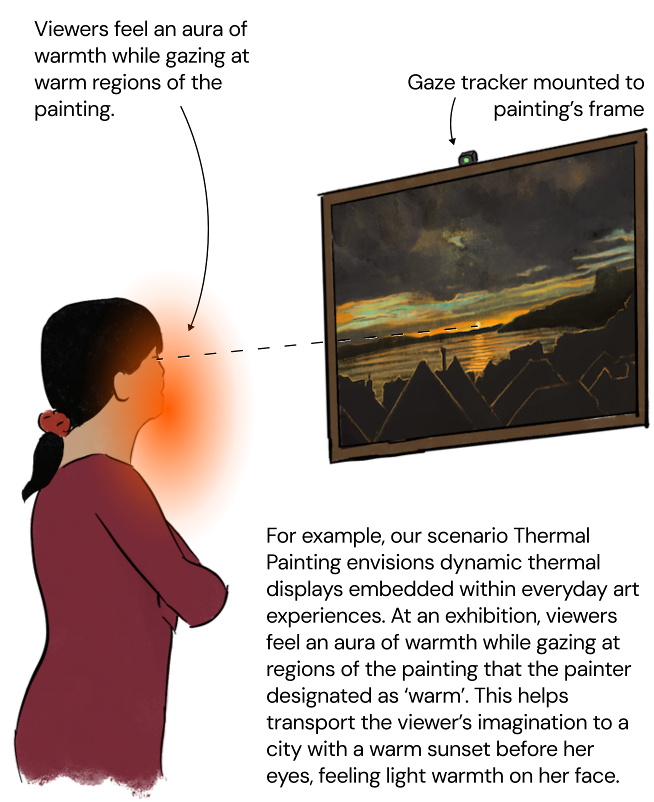
INTRODUCTION

Thermal experience plays a vital role in our daily lives; e.g., we feel social warmth with the warmth of hugs, or feel relaxed in a hot shower. HCI prototypes many thermal display techniques with an emphasis on technical contributions. Recent work at TEI and DIS calls for greater attention to rich, nuanced thermal experiences to inform future thermal designs [32, 111, 112]: Studying people's experiences of Finnish saunas has articulated experiential qualities of heat [112]. Analyzing traditional Chinese Cí poetry has offered a framework for thermal-affective interaction design [32].

Responding to these calls, we sketch interaction design possibilities for thermal experiences in everyday contexts. How might dynamic thermal displays become embedded into everyday activities with friends, self-care, media, and even culinary techniques?

In this pictorial: (1) We map prior work on thermal interactions in two ways, by application area (page 4) and thermal display technique (page 3). Through this, we identify an under-explored niche of thermal display techniques at the intersection of two characteristics: (i) *fast-switching*: rapidly warming or cooling, and (ii) *non-contact*: not requiring wearable devices or touching the heat source. (2) Exploring this niche, our scenarios (pages 6-11) show a range of possibilities for thermal interaction designs leveraging fast-switching non-contact thermal display techniques. (3) Finally, we discuss how these scenarios suggest expansive possibilities for thermal interaction regarding heat as a design material, personalized thermal comfort in shared settings, cultural and emotional associations with heat in everyday contexts, and facial thermal interactions. Overall, this pictorial contributes to mapping the landscape of existing thermal interactions, offers thermal interaction scenarios, and suggests design directions for thermal interaction design.



For example, our scenario Thermal Painting envisions dynamic thermal displays embedded within everyday art experiences. At an exhibition, viewers feel an aura of warmth while gazing at regions of the painting that the painter designated as 'warm'. This helps transport the viewer's imagination to a city with a warm sunset before her eyes, feeling light warmth on her face.

RELATED WORK

Prior works support particular application areas or prototype novel thermal display techniques. Human thermal perception is much slower and lower resolution than vision, and thermal interactions must accommodate this [71, 72, 156]. The time needed to perceive a temperature change depends on many factors including body region, whether it is warming or cooling, stimulus skin area, and rate of temperature change [149, 156].

Thermal application areas

Prior works use thermal feedback for **notifications** discreetly, silently, yet noticeably even in busy environments [9, 10, 19, 79, 105, 120, 122, 154, 188]. For example, ThermEarhook attaches to the ear to present different thermal patterns as notifications [122]. Many thermal notifications are for **driving** contexts, when it is important for vision and hearing to focus on the road [6, 19-22, 108, 164]. For example, one system provides turn navigation cues by warming the corresponding side of the steering wheel [21].

Thermal can represent visual information for **accessibility** [57, 64, 69] and offer tactile feedback for control of prosthetic limbs [70, 81, 167]; e.g., changing temperature based on a virtual painting's colors [57]. Many applications add thermal feedback to **information displays**, for multisensory experiences with typical digital displays [15, 79, 118, 119, 129, 186], a layer of data displayed thermally [36, 140], or enhancing engagement with interactive visualizations [58]. For example, Thermal Icons propose using a set of thermally distinguishable stimuli as "icons" akin to visual icons in mobile media [186].

Many projects augment **creative media**, usually visual [1, 57, 64, 86] but also music [2, 255], for creative, embodied, or emotional effect [45, 62, 93]. For example, Painting Inferno enables painting custom-shaped resistive heaters; paintings become warm in particular regions [165]. Thermofluidics activate thermochromic visuals [194].

Playful designs add thermal feedback to game controllers [58, 88, 100], playfully shift real-world social dynamics with thermal feedback [121], or augment sports spectatorship [135]. HeatCraft's heated belt displays internal body temperature from an ingestible sensor for a playful, intriguing bodily exploration [96]. Many playful experiences augment VR with thermal feedback [26, 137, 138]; e.g., in HeatSense players must deflect invisible obstacles perceived via a thermal glove [137].

Many works use thermal feedback for immersion in **virtual environments** [12, 15, 25, 26, 59, 134, 175, 179], tactility of virtual objects [47, 48, 65, 98], and even wetness illusion [49]. ThermoVR added Peltier elements to a VR headset [134]. FaceHaptics applied wind and warmth to the face from a robotic arm mounted to a VR headset [180]. How visuals influence thermal perception in VR is an area of ongoing study [42, 43]. Thermal feedback also enhances specific virtual environments, such as scuba diving [68] or virtual hell [26].

Educational designs often use thermal feedback to enhance engagement with interactive learning systems. This includes VR training applications, such as for firefighters [113] or welding [147]. Sometimes thermal feedback makes physical simulations more intuitive; e.g., gas thermodynamics [127, 128].

Some applications use thermal feedback for **sustainability**. Feel & See Globe displays global temperatures both visually and thermally [58]. Leaf Heater is a decomposable resistive heater [153]. Personal **thermal comfort** systems support individual thermal comfort in shared office settings [85, 123, 139, 173], potentially reducing overall building energy use.

Thermal perception can be entangled with taste and tactile perceptions. Research has used thermal feedback to relieve **itchiness** [176] and stimulate **taste** [17, 76, 77, 145, 159, 168, 192]. For example, ThermoTumbler changes taste perception with lip thermal feedback [76]. SpiceWare adjusts perceived spiciness of food with by heating/cooling a metal spoon [192].

Physical warmth is associated with interpersonal warmth [63, 182]. Many designs leverage this to augment **remote communication**. As examples, cubble supports long-distance relationships with a colorful, warm cube [89]. Thermal Hugs uses a thermal harness to simulate hugs at a distance [38]. Contrastingly, WARMTH uses cool to express sadness of separation [8]. Huggy Pajama [162], Nakama [181], and TouchMe [94] use warmth to express warmth and care between parent and child at a distance.

Designs support **emotional** expression, reflection, regulation, or stimulation using thermal feedback [84, 130, 144, 169, 171, 184]. Chronometry displays changes in arousal by warming a wristband for self-reflection [170]. Leveraging emotional associations with heat, prior work uses thermal feedback to enrich interactions with a **voice user interface** [83].

Prior works use thermal feedback for **soma** designs, **mindfulness**, and exploring embodied experiences [11, 18, 31, 67, 73]. Ezer et al. designed a somaesthetic wearable using thermal feedback for meditation [31]. Prior work used thermal feedback to support **menstruators** exploring embodied experiences [152] and to convey annoyance [4].

Thermal display techniques

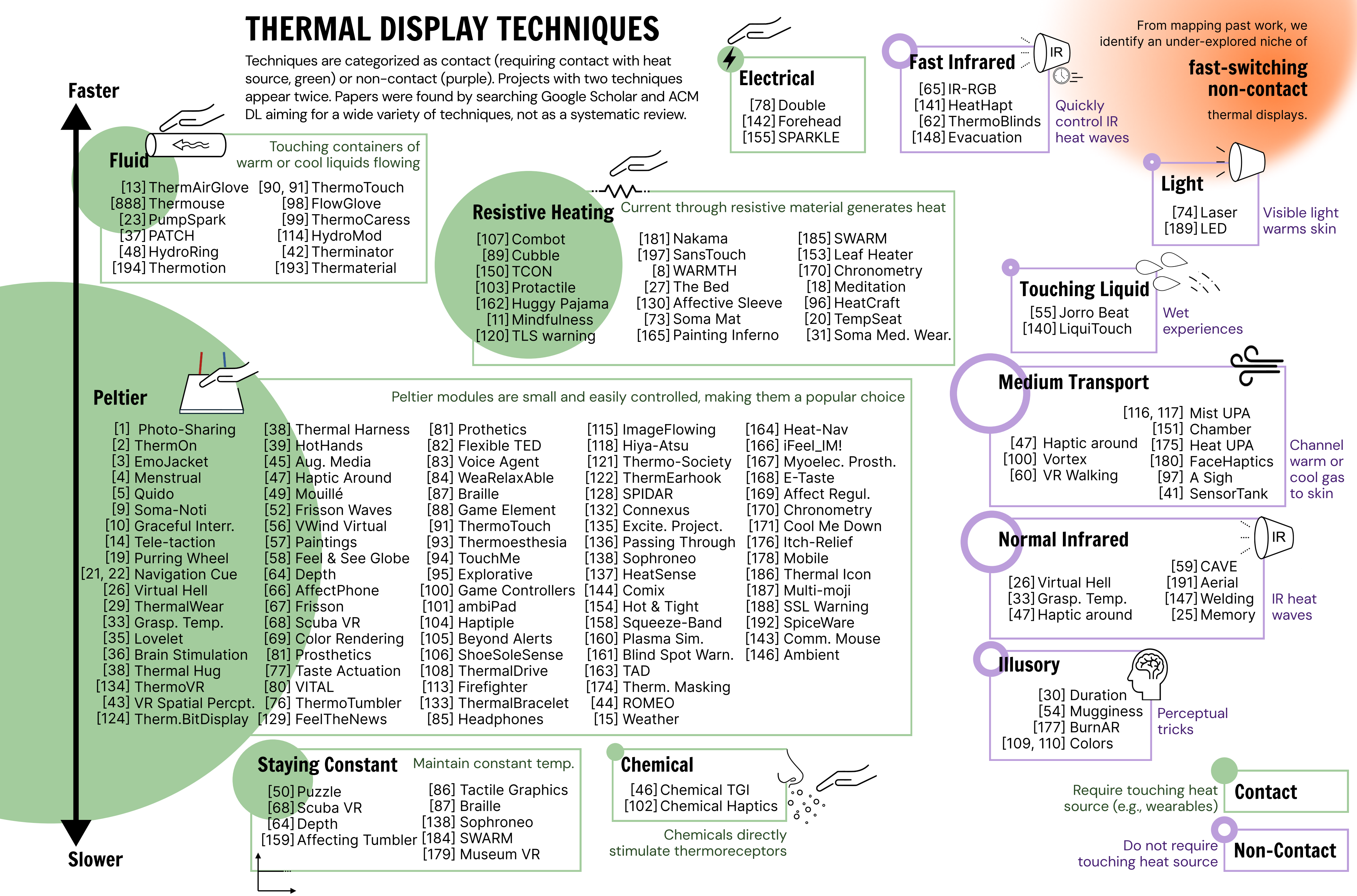
Thermal display techniques are contact or non-contact based on whether the user is in contact with the display or not.

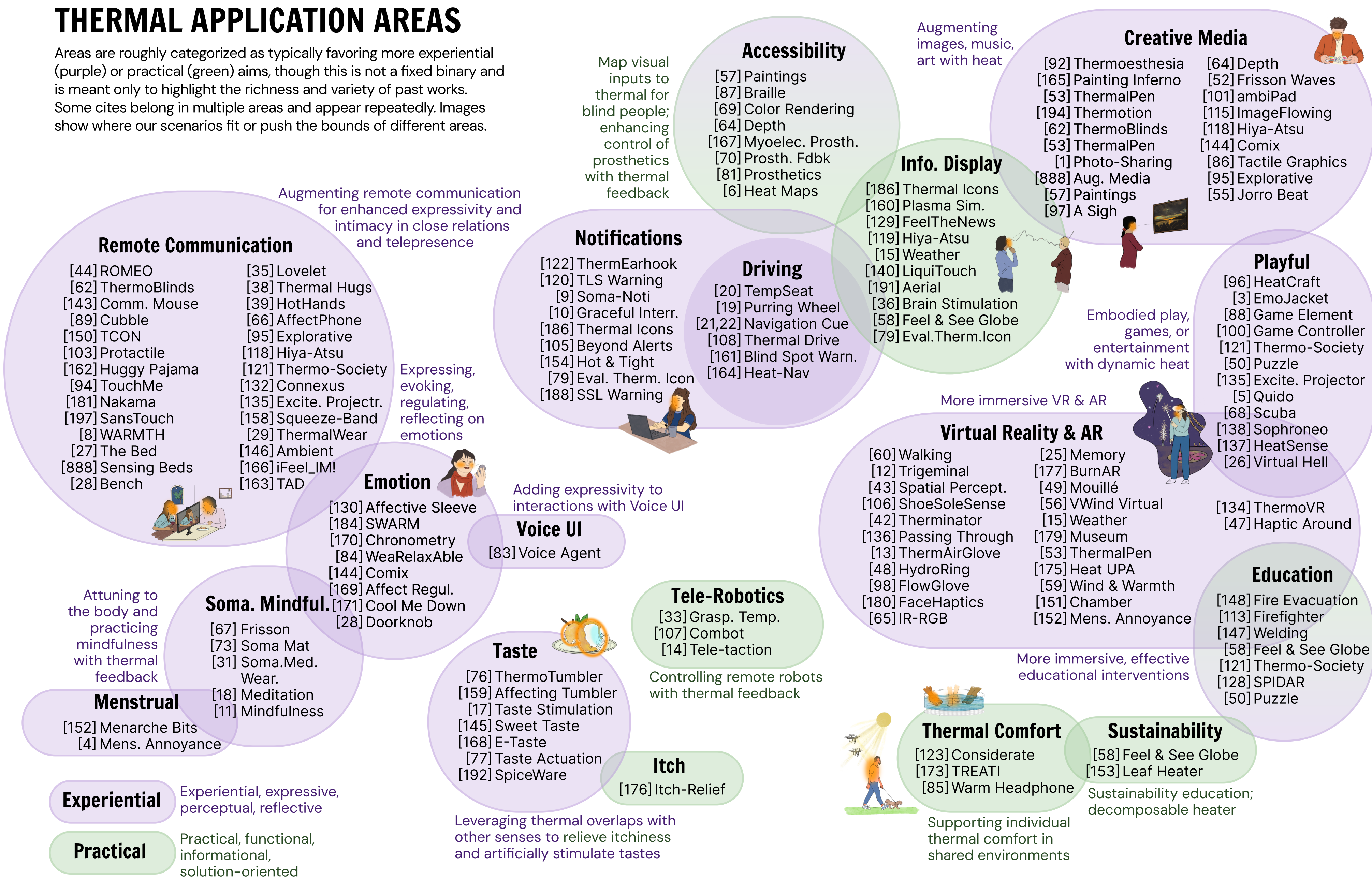
A popular **contact** method is Peltier, which warms and cools based on voltage. Dionisio [26] reproduced warmth in VR with a Peltier module on the forearm. Other contact methods include resistive heating [75, 101, 176], fluid heat conduction [49, 103, 200, 201], directly touching water [57, 146], electrical stimulation [82, 148, 161], chemical stimulation [47, 107], thermal conductivity control [54], gel packs [70], and visual-thermal interactions [80]. For example, Han et al. [49] controlled water temperature flowing through a tube attached to the fingertip to provide rapid thermal feedback.

For **non-contact** thermal feedback, infrared rays are widely used [26, 61, 64, 67, 198]. Like people feel warmth of sunlight or a fireplace, users can experience various thermal sensations with IR. Lécuyer et al. [98] used IR lamps surrounding the user for sunlight in VR. Other non-contact methods include visible light [196], medium transport [32, 48, 110, 123, 157, 181, 186], humidity adjustment [56], ultrasound [78], mist vaporization [122], laser [76], electric arc [161], chemical stimulation [12], and visual-thermal interactions [30, 183, 195]. For example, Nakajima et al. [123] blew cooling mist on skin using ultrasound.

Contact and non-contact methods have tradeoffs. Contact methods require contact, which could be undesirable in some contexts, but can typically change temperature faster and provide localized heat to specific skin regions (e.g., multiple Peltier elements on forearm locations). Non-contact has typically been slower while offering non-spatialized heat over most of the body (e.g., turning on an IR heater and waiting for it to warm up), but can easily accommodate groups of people without wearables. Thus, thermal display techniques should be chosen based on application context.

We identify an under-explored niche of thermal display techniques that are both non-contact and fast-switching. Our map shows emergent techniques in this under-explored space (page 3). By fast-switching, we mean dynamically changing between warm / cool in a couple of seconds, about as fast as typical contact methods. This provides an experience of dynamic warmth that rapidly responds to ongoing user interactions. We avoid defining a strict time frame for "fast-switching" because thermal perception's response times vary depending on many factors including body region, stimulus area, rate of temperature change, etc. [73, 74, 155, 162]; we focus on *experiences* of dynamic, fast-changing warmth.


THERMAL DISPLAY TECHNIQUES
Techniques are categorized as contact (requiring contact with heat source, green) or non-contact (purple). Projects with two techniques appear twice. Papers were found by searching Google Scholar and ACM DL aiming for a wide variety of techniques, not as a systematic review.
Faster
Slower
Fluid
Touching containers of warm or cool liquids flowing
[13] ThermAirGlove
[888] Thermouse
[23] PumpSpark
[37] PATCH
[48] HydroRing
[194] Thermotion
[90, 91] ThermoTouch
[98] FlowGlove
[99] ThermoCaress
[114] HydroMod
[42] Therminator
[193] Thermaterial
Electrical
[78] Double
[142] Forehead
[155] SPARKLE
Fast Infrared
IR
[65] IR-RGB
[141] HeatHapt
[62] ThermoBlinds
[148] Evacuation
Quickly control IR heat waves
From mapping past work, we identify an under-explored niche of
fast-switching non-contact
thermal displays.
Light
[74] Laser
[189] LED
Visible light warms skin
Resistive Heating
Current through resistive material generates heat
[107] Combot
[89] Cubble
[150] TCON
[103] Protactile
[162] Huggy Pajama
[11] Mindfulness
[120] TLS warning
[181] Nakama
[197] SansTouch
[8] WARMTH
[27] The Bed
[130] Affective Sleeve
[73] Soma Mat
[165] Painting Inferno
[185] SWARM
[153] Leaf Heater
[170] Chronometry
[18] Meditation
[96] HeatCraft
[20] TempSeat
[31] Soma Med. Wear.
Touching Liquid
[55] Jorro Beat
[140] LiquiTouch
Wet experiences
Peltier
Peltier modules are small and easily controlled, making them a popular choice
[1] Photo-Sharing
[2] ThermOn
[3] EmoJacket
[4] Menstrual
[5] Quido
[9] Soma-Noti
[10] Graceful Interr.
[14] Tele-taction
[19] Purring Wheel
[21, 22] Navigation Cue
[26] Virtual Hell
[29] ThermalWear
[33] Grasp. Temp.
[35] Lovelet
[36] Brain Stimulation
[38] Thermal Hug
[134] ThermoVR
[43] VR Spatial Percpt.
[124] Therm.BitDisplay
[38] Thermal Harness
[39] HotHands
[45] Aug. Media
[47] Haptic Around
[49] Mouillé
[52] Frisson Waves
[56] VWind Virtual
[57] Paintings
[58] Feel & See Globe
[64] Depth
[66] AffectPhone
[67] Frisson
[68] Scuba VR
[69] Color Rendering
[81] Prosthetics
[77] Taste Actuation
[80] VITAL
[76] ThermoTumbler
[129] FeelTheNews
[81] Prothetics
[82] Flexible TED
[83] Voice Agent
[84] WeaRelaxAble
[87] Braille
[88] Game Element
[91] ThermoTouch
[93] Thermoesthesia
[94] TouchMe
[95] Explorative
[100] Game Controllers
[101] ambiPad
[104] Haptiple
[105] Beyond Alerts
[106] ShoeSoleSense
[108] ThermalDrive
[113] Firefighter
[133] ThermalBracelet
[85] Headphones
[115] ImageFlowing
[118] Hiya-Atsu
[121] Thermo-Society
[122] ThermEarhook
[128] SPIDAR
[132] Connexus
[135] Excite. Project.
[136] Passing Through
[138] Sophroneo
[137] HeatSense
[144] Comix
[154] Hot & Tight
[158] Squeeze-Band
[160] Plasma Sim.
[161] Blind Spot Warn.
[163] TAD
[174] Therm. Masking
[44] ROMEO
[15] Weather
[164] Heat-Nav
[166] iFeel_IM!
[167] Myoelec. Prosth.
[168] E-Taste
[169] Affect Regul.
[170] Chronometry
[171] Cool Me Down
[176] Itch-Relief
[178] Mobile
[186] Thermal Icon
[187] Multi-moji
[188] SSL Warning
[192] SpiceWare
[143] Comm. Mouse
[146] Ambient
Medium Transport
[116, 117] Mist UPA
[151] Chamber
[175] Heat UPA
[180] FaceHaptics
[97] A Sigh
[41] SensorTank
[47] Haptic around
[100] Vortex
[60] VR Walking
Channel warm or cool gas to skin
Normal Infrared
IR
[26] Virtual Hell
[33] Grasp. Temp.
[47] Haptic around
[59] CAVE
[191] Aerial
[147] Welding
[25] Memory
IR heat waves
Illusory
[30] Duration
[54] Mugginess
[177] BurnAR
[109, 110] Colors
Perceptual tricks
Staying Constant
Maintain constant temp.
[50] Puzzle
[68] Scuba VR
[64] Depth
[159] Affecting Tumbler
[86] Tactile Graphics
[87] Braille
[138] Sophroneo
[184] SWARM
[179] Museum VR
Chemical
[46] Chemical TGI
[102] Chemical Haptics
Chemicals directly stimulate thermoreceptors
Contact
Require touching heat source (e.g., wearables)
Non-Contact
Do not require touching heat source



THERMAL APPLICATION AREAS
Areas are roughly categorized as typically favoring more experiential (purple) or practical (green) aims, though this is not a fixed binary and is meant only to highlight the richness and variety of past works. Some cites belong in multiple areas and appear repeatedly. Images show where our scenarios fit or push the bounds of different areas.
Map visual inputs to thermal for blind people; enhancing control of prosthetics with thermal feedback
Accessibility
[57] Paintings
[87] Braille
[69] Color Rendering
[64] Depth
[167] Myoelec. Prosth.
[70] Prosth. Fdbk
[81] Prosthetics
[6] Heat Maps
Augmenting images, music, art with heat
Creative Media
[92] Thermoesthesia
[165] Painting Inferno
[53] ThermalPen
[194] Thermotion
[62] ThermoBlinds
[53] ThermalPen
[1] Photo-Sharing
[888] Aug. Media
[57] Paintings
[97] A Sigh
[64] Depth
[52] Frisson Waves
[101] ambiPad
[115] ImageFlowing
[118] Hiya-Atsu
[144] Comix
[86] Tactile Graphics
[95] Explorative
[55] Jorro Beat
Info. Display
[186] Thermal Icons
[160] Plasma Sim.
[129] FeelTheNews
[119] Hiya-Atsu
[15] Weather
[140] LiquiTouch
[191] Aerial
[36] Brain Stimulation
[58] Feel & See Globe
[79] Eval.Therm.Icon
Augmenting remote communication for enhanced expressivity and intimacy in close relations and telepresence
Remote Communication
[44] ROMEO
[62] ThermoBlinds
[143] Comm. Mouse
[89] Cubble
[150] TCON
[103] Protactile
[162] Huggy Pajama
[94] TouchMe
[181] Nakama
[197] SansTouch
[8] WARMTH
[27] The Bed
[888] Sensing Beds
[28] Bench
[35] Lovelet
[38] Thermal Hugs
[39] HotHands
[66] AffectPhone
[95] Explorative
[118] Hiya-Atsu
[121] Thermo-Society
[132] Connexus
[135] Excite. Projectr.
[158] Squeeze-Band
[29] ThermalWear
[146] Ambient
[166] iFeel_IM!
[163] TAD
Notifications
[122] ThermEarhook
[120] TLS Warning
[9] Soma-Noti
[10] Graceful Interr.
[186] Thermal Icons
[105] Beyond Alerts
[154] Hot & Tight
[79] Eval. Therm. Icon
[188] SSL Warning
Driving
[20] TempSeat
[19] Purring Wheel
[21,22] Navigation Cue
[108] Thermal Drive
[161] Blind Spot Warn.
[164] Heat-Nav
Embodied play, games, or entertainment with dynamic heat
Playful
[96] HeatCraft
[3] EmoJacket
[88] Game Element
[100] Game Controller
[121] Thermo-Society
[50] Puzzle
[135] Excite. Projector
[5] Quido
[68] Scuba
[138] Sophroneo
[137] HeatSense
[26] Virtual Hell
Expressing, evoking, regulating, reflecting on emotions
Emotion
[130] Affective Sleeve
[184] SWARM
[170] Chronometry
[84] WeaRelaxAble
[144] Comix
[169] Affect Regul.
[171] Cool Me Down
[28] Doorknob
Adding expressivity to interactions with Voice UI
Voice UI
[83] Voice Agent
More immersive VR & AR
Virtual Reality & AR
[60] Walking
[12] Trigeminal
[43] Spatial Percept.
[106] ShoeSoleSense
[42] Therminator
[136] Passing Through
[13] ThermAirGlove
[48] HydroRing
[98] FlowGlove
[180] FaceHaptics
[65] IR-RGB
[25] Memory
[177] BurnAR
[49] Mouillé
[56] VWind Virtual
[15] Weather
[179] Museum
[53] ThermalPen
[175] Heat UPA
[59] Wind & Warmth
[151] Chamber
[152] Mens. Annoyance
[134] ThermoVR
[47] Haptic Around
Attuning to the body and practicing mindfulness with thermal feedback
Soma. Mindful.
[67] Frisson
[73] Soma Mat
[31] Soma.Med. Wear.
[18] Meditation
[11] Mindfulness
Menstrual
[152] Menarche Bits
[4] Mens. Annoyance
Tele-Robotics
[33] Grasp. Temp.
[107] Combot
[14] Tele-taction
Controlling remote robots with thermal feedback
Taste
[76] ThermoTumbler
[159] Affecting Tumbler
[17] Taste Stimulation
[145] Sweet Taste
[168] E-Taste
[77] Taste Actuation
[192] SpiceWare
Itch
[176] Itch-Relief
Leveraging thermal overlaps with other senses to relieve itchiness and artificially stimulate tastes
Education
[148] Fire Evacuation
[113] Firefighter
[147] Welding
[58] Feel & See Globe
[121] Thermo-Society
[128] SPIDAR
[50] Puzzle
More immersive, effective educational interventions
Thermal Comfort
[123] Considerate
[173] TREATI
[85] Warm Headphone
Supporting individual thermal comfort in shared environments
Sustainability
[58] Feel & See Globe
[153] Leaf Heater
Sustainability education; decomposable heater
Experiential
Experiential, expressive, perceptual, reflective
Practical
Practical, functional, informational, solution-oriented

Initial Prototype →

We began exploring thermal interactions by adapting a technique from our prior work [62] that enabled us to experience fast-switching, non-contact warmth.

Shutters closed: neutral

Shutters open: heat

Reflection →

Reflecting on our everyday life experiences with thermal sensations. Our team is from Japan, India, and the US.

- Coziness of a Japanese kotatsu table with heater and blanket in winter
- Inability to drink tea if it is too hot
- Preference for very hot drinks, showers, space heaters, saunas
- Moxibustion (hot herbal smudge on acupuncture needles)
- Finnish saunas (see also Moesgen et al. [112]))

Sometimes we tread carefully beyond our own cultural heritage, focused specifically on thermal perceptions, not claiming insight into cultural or social significance.

Brainstorming →

Relaxation

Environment

Emotional associations

Notifications

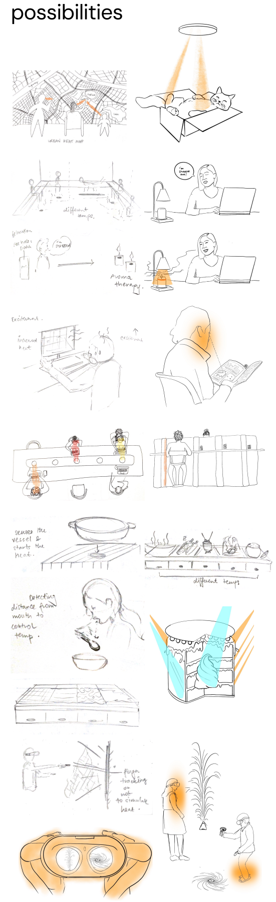
Directional feedback

Play

Clusters emerged from our brainstorm.

Concepts →

Sketching interaction possibilities



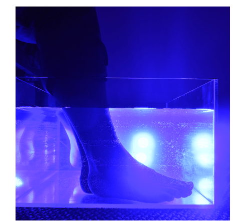
Scenarios

Illustrated Scenarios:

We discussed, adapted, refined, and iterated on the concepts to develop illustrated scenarios of thermal interaction possibilities. Our scenarios aim to go beyond already-existing thermal displays in prior work, yet stay within the realm of technically possible, to help expand the design space.

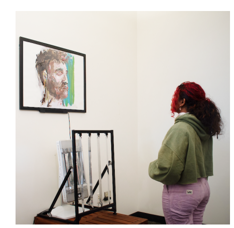
Prototyped Scenarios:

We prototyped some scenarios to demonstrate technical feasibility. Ongoing studies of people's rich and varied experiences with these designs are part of ongoing and future work, outside the scope of this pictorial.



Thermal Foot Bath

Thermal Movie



Thermal Painting

PROCESS

We combined prototyping, reflecting on experiences of warmth, and brainstorming. We use technical approaches of prototyping and designerly approaches of scenarios. This mixed-methods approach is motivated by prior work [32, 112] highlighting the wealth of thermal display techniques in past work and calling for greater attention to interaction design of thermal experiences. We developed specific scenarios based on personal interest, such as Bheda feeling homesick (VR Diwali scenario), Ichihashi working at the computer (Heat as Notification scenario), or other collaborations with painters (Thermal Painting).

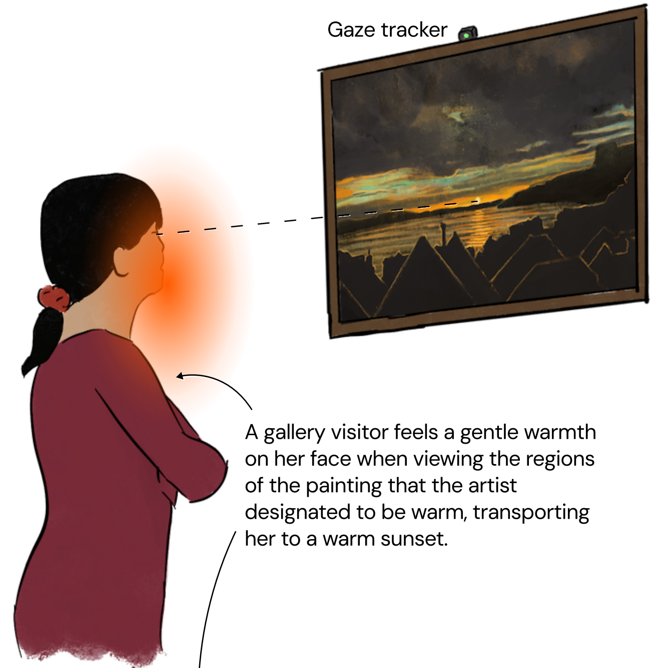
SCENARIOS

Thermal Painting

Gaze-based thermal feedback embeds thermal sensations into conventional visual media for more immersive and emotional experience. Viewers experience different thermal sensations based on the region of the painting they gaze at.

Our prototyped scenario enables viewers to feel varying warmth for each part of the painting in a natural way. The setup mimics ordinary art exhibitions; i.e., visitors enter a venue, appreciate a painting in front of them, and move to the next.

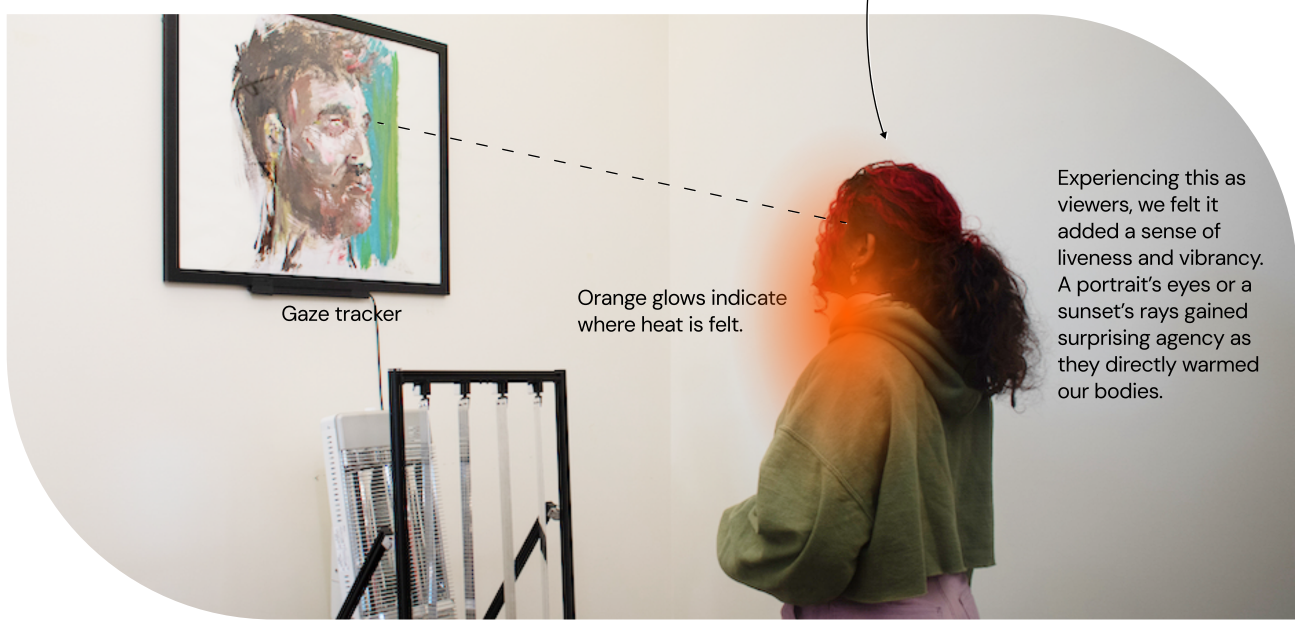
While prior work uses algorithmically predetermined color-temperature mappings [57, 64, 69], we envision artists specifying warm and cool regions according to their creative decisions.



A gallery visitor feels a gentle warmth on her face when viewing the regions of the painting that the artist designated to be warm, transporting her to a warm sunset.

While painting, the artist decides to add a sensory layer of heat for viewers.

The artist assigns heat to the portion of the painting she believes should make the viewer experience warmth.



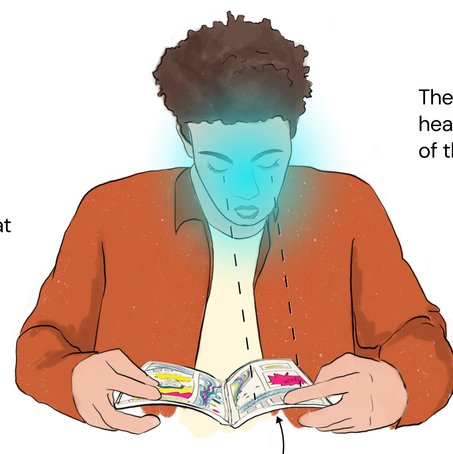
Experiencing this as viewers, we felt it added a sense of liveness and vibrancy. A portrait's eyes or a sunset's rays gained surprising agency as they directly warmed our bodies.

Heat as Page Highlights

While designing comic books, magazines, or other text-based media, artists can designate areas of the page to emit certain warm or cold temperatures triggered by the reader's gaze. Artist-designated, gaze-based thermal feedback embeds thermal sensations into conventional visual media for more immersive and emotional experience.

Artist assigns cool to this scene to denote tranquility

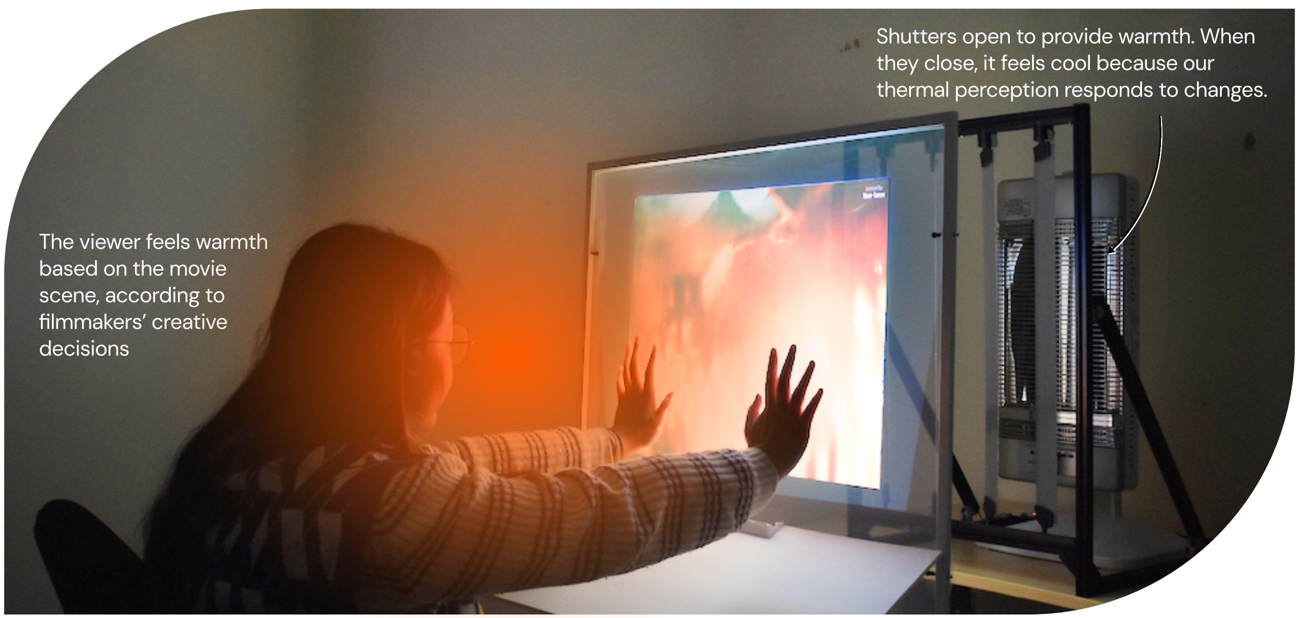
Artist assigns heat to this charged scene



The reader feels cold and heat, amplifying the drama of the story

When reading this panel, he feels the refreshing, calm cool of the water

He feels the sudden blast of warmth of the explosion when his gaze shifts to reading the next panel



Thermal Movie

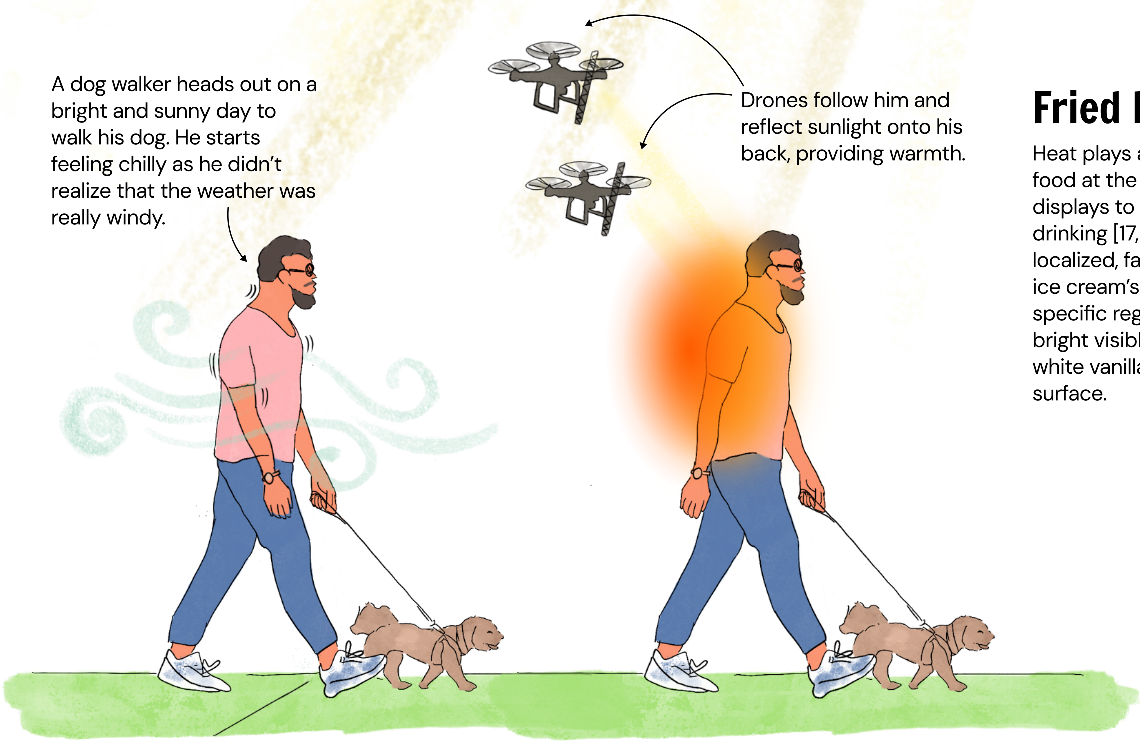
With fast-switching non-contact thermal feedback, people can experience a wide variety of thermal events augmenting the scenes of the film. This can include dramatic heat from explosions, or the relaxing warmth of a fireside scene. This simple implementation adapted from Ichihashi et al. [61, 62] could be used in movie theaters, auditoriums, or in-home theater systems.

Future work could create software plugins allowing movies, documents, images, and audio files to be overlaid with assigned thermal feedback according to temporal and spatial patterns of the creators' choosing.

Experiencing Thermal Movie, we felt it added a visceral and entertaining excitement to dramatic fiery scenes. Future work could further explore how thermal feedback could be used for a variety of creative effects in different kinds of film, whether to convey emotional warmth, the heat of anger or passion, hot climates, the heat of embarrassment, or more abstract sensory patterns for abstract films.

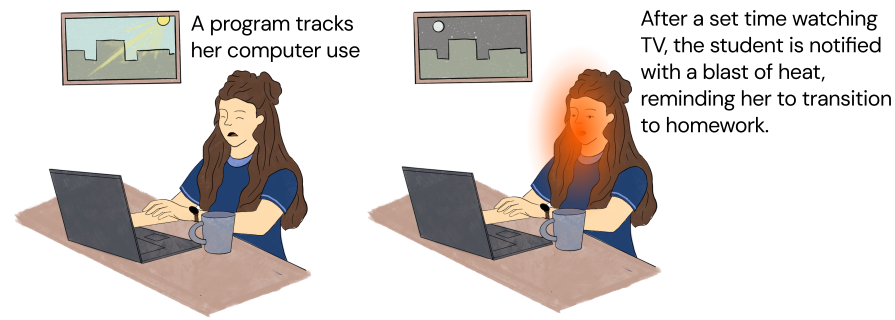
Sunlight Reflecting Drones

Drones with steerable mirrors follow the dog walker to reflect sunlight and provide interactive thermal feedback in outdoor scenarios. By utilizing natural heat sources, thermal displays can go outdoors without power for the heat. Beyond this application, dynamically reflecting sunlight with drones could open up creative display possibilities.



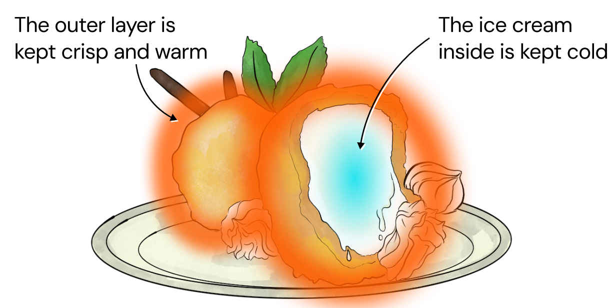
Heat as Notification

A college student starts watching TV during the day and loses track of time. She often gets distracted during her leisure time and feels less productive because of it. So, she has set up a program to track her screen time and trigger reminders according to the schedule she has programmed. Unique qualities of non-contact heat can offer non-intrusive, yet effective notifications that support people by reminding them or prompting certain actions according to the individual user's preferences and goals.



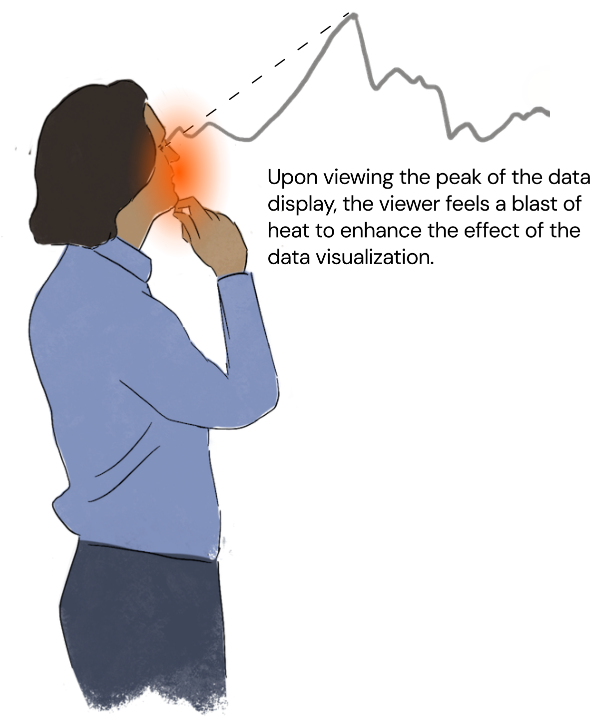
Fried Ice Cream: Hot & Cold Zones

Heat plays an important role in the quality of food, its texture, and how it feels to eat it. The right food at the right temperature can evoke a multitude of emotions. Past work has used thermal displays to augment food experiences by providing heat on the human body when eating or drinking [17, 76, 159, 168, 192]. Going beyond past work, we believe thermal displays can apply localized, fast-switching, non-contact heat on food itself to expand this design space. Here, fried ice cream's complex temperature and texture is enhanced with localized heat and cool to specific regions of the food, providing a more pleasurable culinary experience. We envision using bright visible lights to dramatically spotlight the food and selectively heat food based on color; white vanilla ice cream would reflect more visible light and stay cooler than the darker fried surface.



Thermal Data Display

A person visits an interactive data display exhibit which uses heat to add a multimodal layer to the data. This can present more embodied data visualizations drawing from data feminism [24]. For example, we envision that heat could add visceral emphasis to data displays on topics such as climate change, gun deaths, or wildfires.



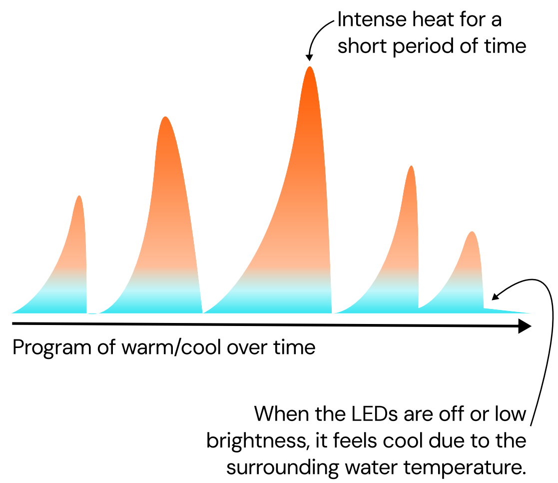
Social Foot Bath

Friends go to the sauna together and want to share a hot foot bath, but they have very different temperature preferences. So, each person's region of the water is a different temperature. The local temperature can be adjusted instantaneously for personalized comfort.

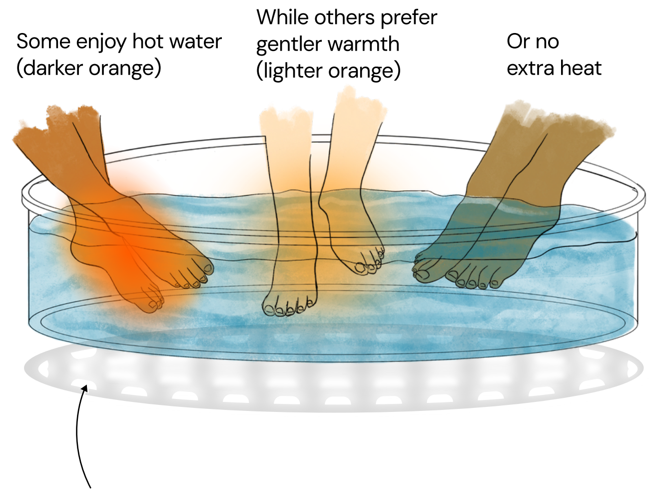
Water offers a sense of togetherness as friends can feel the presence and movement of one another through waves and water flow. Non-contact heat through light introduces personalized hedonic experiences while preserving this sense of togetherness.

Experiencing Social Foot Bath, it felt surprising and novel for the temperature to change instantaneously, and it felt playful to share the water bath with others, encouraging gentle splashing.

The local heat can dynamically shift over time by adjusting the LED brightness, offering novel hedonic and embodied experiences of rapidly changing water temperature.



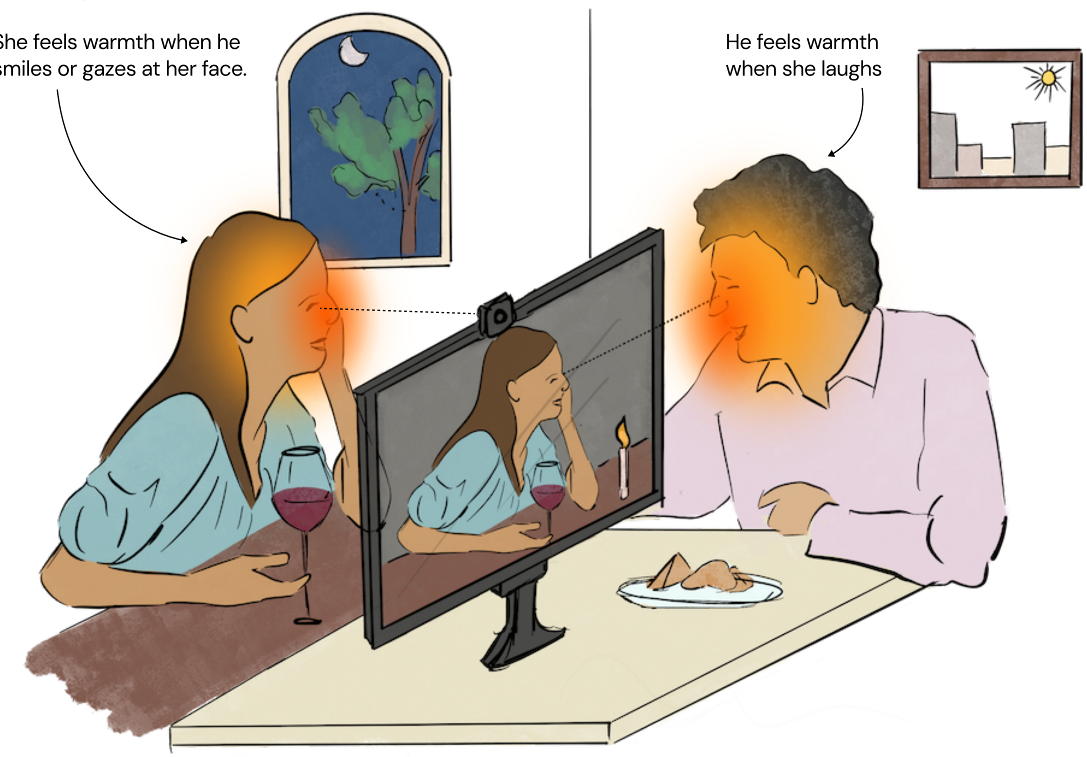
Note: The different temporal capabilities of technologies and perception modalities must be accommodated when designing thermal interactions [71, 72] such as composing temporal sequences. Thermal perception is much slower than vision [156]. The duration of time needed to perceive a temperature change depends on many factors including body region, whether it is warming or cooling, stimulus area, and rate of temperature change [149, 156].



Densely packed LEDs around the rim of the bath provide heat. The water changes perceived temperature rapidly by controlling the intensity of light illuminating the feet, without changing the actual water temperature.

Candlelit Dinner

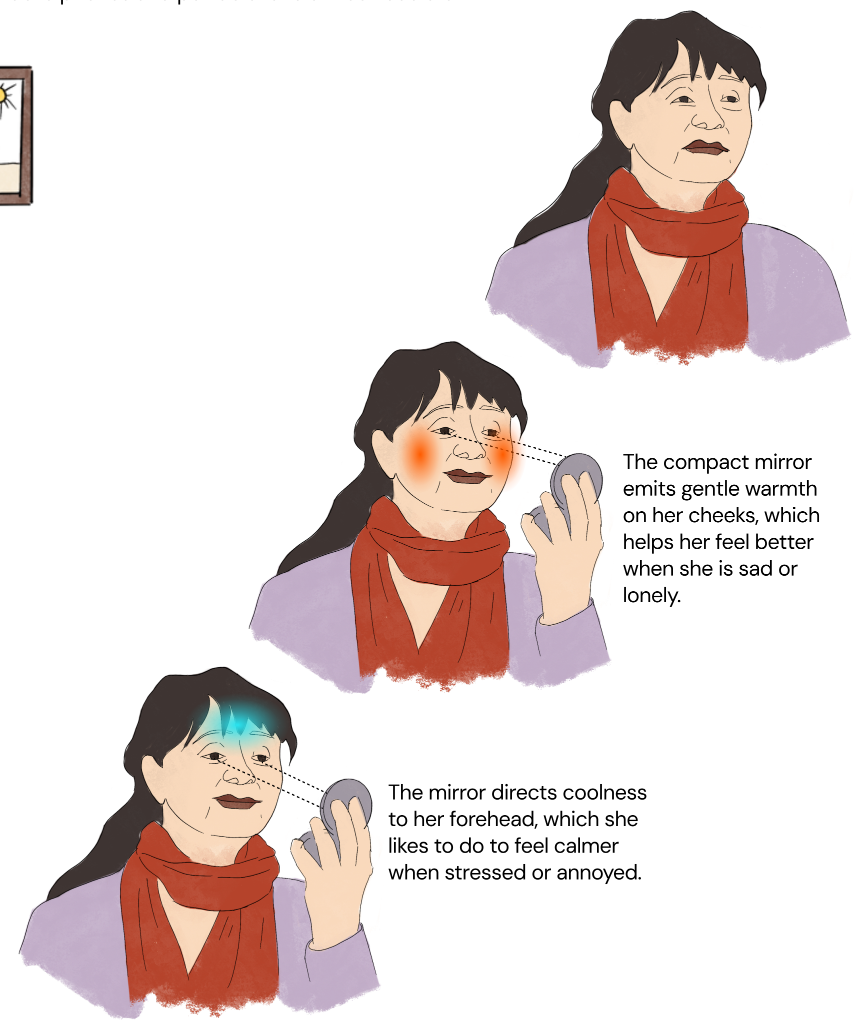
A couple in a long distance relationship uses heat to communicate their feelings of love and warmth. Thermally-augmented communication can be designed for a variety of interpersonal relationships, contexts, and cultures. As another example, thermal interactions could support more warmth in team meetings by responding to appreciation, laughter, or gaze.



Calming Contact Mirror

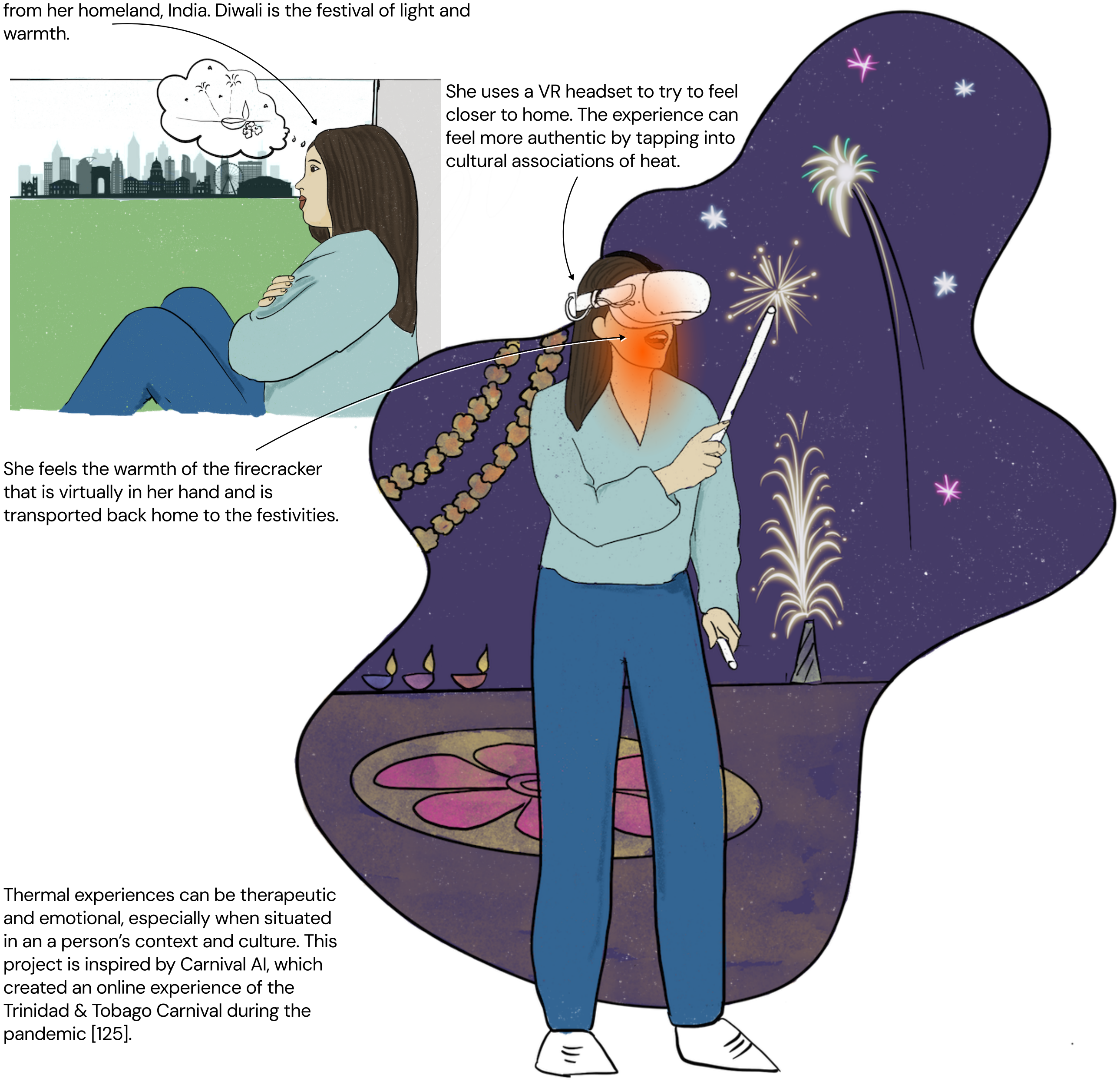
A contact mirror offers warm and cool sensations to different regions of the face, designed to foster self-care, comfort, and calm during moments of sadness or anxiety. Thermal experiences are linked to emotions: Warmth can be associated with social connection and alleviating loneliness [7, 34, 183], while cool can be refreshing and may help calm down [75].

The face is the most heat-sensitive part of the body [157], so even relatively weak temperature changes are quite perceptible. Although challenging to provide localized thermal feedback over varied distances from a portable device, we envision that a camera for facial recognition and a fan with heating elements and mist could offer localized heating / cooling, adapting technology from mobile phones and portable fans or neck coolers.



VR Diwali: Cultural Warmth

An international student feels homesick and misses festivals from her homeland, India. Diwali is the festival of light and warmth.



She uses a VR headset to try to feel closer to home. The experience can feel more authentic by tapping into cultural associations of heat.

She feels the warmth of the firecracker that is virtually in her hand and is transported back home to the festivities.

Thermal experiences can be therapeutic and emotional, especially when situated in an a person's context and culture. This project is inspired by Carnival AI, which created an online experience of the Trinidad & Tobago Carnival during the pandemic [125].

DISCUSSION

We discuss how these scenarios open possibilities for thermal interaction design and offer design directions for future work.

Engaging heat as a design material with sketching and prototyping

Past work calls for engaging heat as a design material through varied methods. Moesgen et al. study experiences of Finnish saunas to articulate qualities of heat as a design material [112], building on past work on heat as an expressive medium [95]. Feng et al. analyze thermal descriptions in traditional Chinese Cí poetry to unpack ways warm and cool can evoke affective meanings [32]. Jonsson et al. do soma design and call for attending to aesthetic and experiential qualities of heat [73].

We engage these calls as an opportunity to build on the rich body of past work in HCI that has prototyped many thermal display techniques. In our pictorial, we map past work on both thermal application areas and thermal display techniques. By both sketching and technical prototyping, we show a wide range of thermal interaction scenarios. These scenarios foreground thermal *experiences* by highlighting where heat is felt (orange glows) and interaction contexts.

We use this mixed-methods approach to show the potential of non-contact, dynamic thermal techniques to support rich everyday thermal experiences. For example, our scenarios Thermal Painting and Thermal Data Display leverage heat as an expressive medium to enhance viewers' experiences of art or data in museums, dynamically adjusting heat in response to the viewer's gaze. Typical contact-based techniques (e.g., Peltier elements) would require visitors to put on wearables or touch a heat source to feel dynamic (fast-switching) heat, which could detract from some public settings, and the heat would be in one skin region only. Fast-switching non-contact thermal display techniques enable more holistic thermal interactions that better mesh with everyday contexts and activities. It is through combining technical and designerly approaches—mapping related work both by application area and thermal display technique, and developing scenarios both by sketching and technical prototyping—that we were able to identify and explore this unique potential for thermal interactions.

For engaging heat as a design material, we suggest mixed methods: engaging both embodied interaction design considerations alongside and in tandem with technical considerations of thermal display techniques.

Personal thermal dis/comfort in shared contexts

Extreme heat and cold can be life-threatening; maintaining a comfortable body temperature is not only pleasant, we feel thermal dis/comfort at a deep level. Yet, people may also have more complex thermal preferences. For example, Moesgen et al. articulate `aesthetics of discomfort' in Finnish sauna experiences, where uncomfortably intense too-hot leads to pleasurable warm relief [112]. In our process, enjoying discomfort also arose when reflecting on our past thermal experiences (see Process), with one author enjoying saunas, showers, and tea so hot as to be uncomfortable or almost burning, while another feeling a need to avoid extremes and stay within a safe zone of gentle warmth and cool. Responding to this, our scenarios brainstorm ways of supporting differing thermal preferences and comfort zones in shared contexts.

Our pictorial shows how designers can use thermal displays to support individualized thermal preferences for co-located individuals. Many techniques support thermal comfort; e.g., air conditioners, heaters, or clothing. The unique aspect we explore is that dynamic (fast-switching), spatial control of non-contact heat allows for personalized thermal experience for each collocated person without personal devices or clothes. This enables both shared and individual experiences with a sense of togetherness, intimacy, security, or comfort.

For example, the Social Foot Bath allows people to enjoy their preferred water temperature, but also share the social experience of the foot bath; people can enjoy cooler or warmer water while feeling each other's presence and movement through the water. In the Sunlight Reflecting Drones scenario, people can experience a personalized thermal climate while spending time together outdoors.

We suggest exploring **localized, non-contact thermal displays for shared-yet-personalized experiences** for gatherings with different temperature preferences. Future design research can build on studies of personal comfort systems to provide personalized thermal comfort in shared offices, potentially reducing the overall energy used to heat or cool the building (e.g., [51, 131, 172, 196]).

Situating thermal interaction designs in diverse emotional, cultural everydays

Based on thermal descriptors in traditional Chinese Cí poetry, Feng et al. outline ways thermal experiences can mediate emotions, such as augmenting or contrasting emotions [32]. Our scenarios explore thermal-emotion associations, showing fast-switching non-contact heat's potential to dynamically respond to social emotional cues. While prior works support emotional experiences through heat (see Related Work: Application Areas), we suggest exploring **dynamic, localized, non-contact heat to help evoke emotions closely linked to one's own and others' actions.**

For example, Candlelit Dinner adds physical warmth to long-distance smiles or laughs over video call, augmenting moments of social emotional warmth with physical warmth, time-synced with the conversation flow. Compact Mirror provides dynamic warm and cool, targeting the face. Looking at oneself in the mirror while feeling warmth from the mirror implicitly associates the warmth with a moment of self-reflection and self-care. Here, warmth could contrast and mitigate feelings of loneliness, while cool could contrast and mitigate feelings of anger or annoyance. While poetry [32] may often seek to highlight and convey emotions, in everyday life people may often seek to calm, soothe, or regulate emotions.

Our scenarios also highlight opportunities for how **designers can consider cultural associations and meanings of heat to situate thermal interactions in everyday contexts.** The VR Diwali scenario shows fast-switching heat's unique qualities, augmenting VR immersion in a cultural celebration. Designers should not only ensure thermal interactions are culturally appropriate, they can also find new opportunities to design for specific cultural practices, rituals, or meanings of heat.

Our process drew inspiration from our cultural experiences in Japan, India, and the US. Our pictorial helps open design opportunities for how cultural associations and meanings of heat in diverse cultures can inspire designing novel thermal interactions reflecting people's relationships with heat from various perspectives. Again, these are just a few examples of many possibilities. Fast-switching, non-contact heat can suggest cultural meanings and new thermal experiences for groups of people in diverse settings.

Beyond `the everyday', we highlight designing for diverse, varied everyday<u>s</u> of different contexts, cultures, emotions, and individual preferences—to open thermal design possibilities.

Designing facial thermal interactions

Faces are thermally sensitive [157] and warming/cooling the face influences overall sense of body temperature [16]. Prior work has explored facial thermal interactions (e.g., [180]). Dynamic non-contact thermal displays are uniquely well suited for facial thermal interactions because they do not require people to put something directly on their face.

Our scenarios explore facial interactions, such as Compact Mirror, Candlelit Dinner, and Heat as Page Highlights. We suggest exploring **dynamic non-contact thermal display techniques for facial thermal interactions.**

LIMITATIONS & FUTURE WORK

Future work should explore more cooling scenarios and further investigate technical feasibility, including energy estimates, user-display proximity requirements, and the impact of varied environmental ambient temperatures on user experience. Our ongoing and future work studies people's experiences with related designs; without those findings in this pictorial, our discussion offers promising directions for future work to explore, not evidenced guidelines.

This pictorial does not claim that this set of scenarios represents *the* designs that should be built and evaluated; rather, the contribution of this pictorial is to showcase a range of thermal interaction possibilities to inform future design research. These scenarios are only a few possibilities.

Our scenarios span a range of application areas (page 4), yet do not touch areas with the least prior works in our map. Although a few of our scenarios include cooling, future work can explore more cooling interactions. Future work can explore thermal interactions for personal thermal comfort for reducing overall building energy use for sustainability, building on prior work outside HCI (e.g., [51, 139, 195]).

Future work should explore more design possibilities, more thermal techniques, and study people's experiences with these designs.

CONCLUSION

To help reflect on and expand the design space of thermal interactions, we offer maps of thermal design applications and thermal display techniques. From this, we identify an opportune area of fast-switching, non-contact thermal display techniques that can provide dynamic thermal sensations without requiring the user to directly touch the display. In this niche, our scenarios showcase a range of design possibilities for thermal experiences in everyday contexts. We offer design directions for (a) engaging heat as a design material through both sketching and prototyping, (b) personalized thermal comfort in shared contexts with localized non-contact thermal displays, (c) designing for cultural and emotional associations with heat in diverse everydays, and (d) designing facial thermal interactions.

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