



Towards Psychosomatic Architecture

Attuning Reactive Architectural Materials Through Biofeedback

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The built environment is known to affect human health and wellbeing. Yet architecture does not respond to our bodies or our minds. It tends to be static, ignoring the human occupant, their mood, behaviors, and emotions. There is evidence that this monotony of average space is harmful to human health. Additionally, differences in gender, race, and cultural conditions vary the perception of and preferences for temperature and color. To improve the psychosomatic relationship with architectural spaces, there arises the necessity for it to have a greater range of spatial reactivity and better support for personalized thermoregulation and aesthetics. This paper proposes an architecture that operates like a mood-ring, one that creates rich feedback between architecture and occupant towards individualized reactivity and expression. *Sentient Concrete (Image 1)* is a prototype of a thermochromically treated concrete panel that is thermally actuated by embedded electromechanical systems and can dynamically produce localized thermally reactive responses. It serves as a test case for outlining further research agendas and possible design frameworks for psychosomatic architecture.

Cover Image Digital model of
Sentient Concrete panel: Point
cloud mesh of surface topology
embedded with thermal pathways.
Dana Cupkova, Dan Cascaval

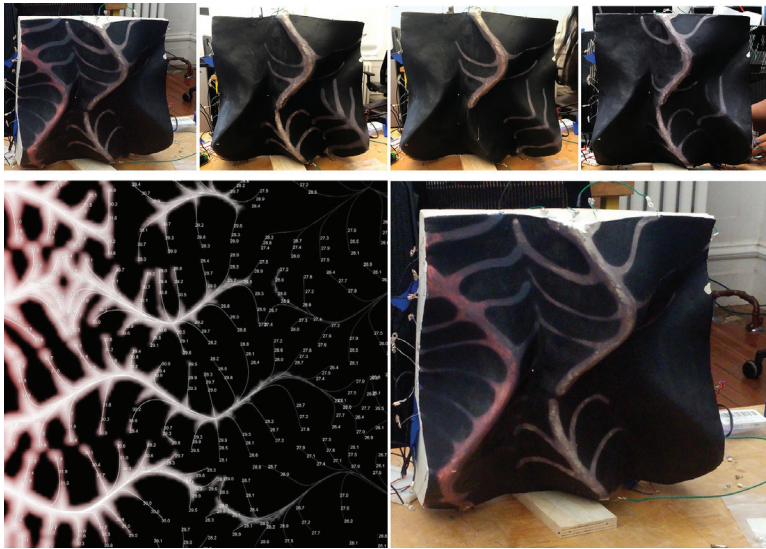


Image 1 Sentient Concrete Panel and thermal network map (Cupkova, Byrne and Cascaval, 2018): The ambition was to prototype an architectural environment that uses energy and matter to tap into sensorial subjectivity as part of the aesthetic and ecological experience. Sentient concrete is a panel prototype that is thermally actuated by its geometry and an embedded electromechanical system that can dynamically produce localized thermally reactive and thermochromic responses on its surface.

Vision

Buildings should operate just like living systems: change their color and self-regulate temperature, tightly coupled with the environment. The psychosomatic architecture is interested in new forms of materiality that draw a connection between energy, human perception, and living systems in architecture, to propose new forms of embedded material responsiveness for architectural surfaces that affect relationships between human health, thermoregulation, aesthetics, and energy usage. Energy is both empirical and perceptual. Inspired by research on human emotional reactivity that can be mapped through temperature gradients of the human body, we explore design through the passive thermoregulation of surfaces. The ambition of this research is to create a new generation of adaptive materials that react to changing conditions of human presence and emotion, to create holistic, responsive, and slow-phased surface changes within the built environment. The intent is to shape and color standard material systems, such as concrete, into surface geometries that are responsive to human tactility and thermal change through the use of convection and thermochromics.¹ Further, the intention is to embed electromechanical systems within these built surfaces to enable directed communication based on biofeedback and sensing.²

- 1 Cupkova, Dana and Patcharapit Promoppatum. 2017. "Modulating Thermal Mass Behavior Through Surface Figuration." In *ACADIA 2017: Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, Cambridge, 2017. 202 – 211. ACADIA Publishing Company
- 2 Cupkova, Dana, Daragh Byrne and Dan Cascaval. 2018. "Sentient Concrete: Developing Embedded Thermal and Thermochromic Interactions for Architecture and Built Environment." In *Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference – Volume 2*, Beijing, 2018. 17 – 19.

- 3 Mahnke, Frank H. 1996. *Color, Environment, and Human Response*. Hoboken: Wiley
- 4 Frieling, Heinrich. 1975. *The Color Mirror: The Quicktest for Character Diagnosis with the Colors of the "Frieling-Test"*. Berlin: Musterschmidt.
- 5 Kopec, Dak A. 2006. *Environmental Psychology for Design*. New York: Fairchild.
- 6 Meerwin, Gerhard, Bettina Rodeck and Frank H. Mahnke. 2007. *Color - Communication in Architectural Space*. Basel: Birkhäuser Basel.
- 7 Mahnke, 1996.

Psychological effects of color on human perception have been studied. Human brain processing is tightly linked to the perceptual changes in its environment.³ Color and temperature have a deep effect on our sensory perception. The sensory and emotional states of mind affect physical factors of human health and learning development,⁴ and cultural background, difference in age, gender impact perception, and environmental psychology of design.⁵ This framework constitutes a potential to build a more robust communication between humans and their environment: a study of psychosomatic feedback⁶ rooted in individualized art-based production that would give deeper foundation to treat the everyday design of living environments as an art form attuned with the human mind. Traditionally, the knowledge of color has been used in architecture within the framework of associative symbolic design related to different levels of stimulation. For example: red is arousing, passionate, and provocative; green is balancing, natural, calm, and inspires feelings of simplicity, security, and balance. Over-stimulation or under-stimulation of human sensory experiences can be produced by color range, intensity of patterns, feelings of thermal comfort, and other parameters related to aesthetics of spatial experience. Spatial stimuli have been linked to changes in breathing, increased heart rate, and changes in pulse and blood pressure.⁷ Environmental under-stimulation has been linked to restlessness, irritability, and difficulty concentrating. These issues are extremely relevant to the culture of the built environment, educational spaces, and architecture at large. Color and pattern application are design parameters generally used as static design expressions. Psychosomatic architecture intends to explore these parameters within a dynamic framework, related to individualizing human presence in space. The investigation is rooted in design and development of reactive material systems, combining the use of color and surface temperature with ability for greater reactive attunement to the psychological sensory human frameworks and expression of new artistic character.

The Innovation for the Everyday

- 8 Fox, Michael, ed. 2016. *Interactive Architecture: Adaptive World*. New York: Princeton Architectural Press

Investigations to date from art, design, and architecture typically imagine reactive spaces as kinetically actuated physical infrastructure.⁸ *Sentient Concrete* prototype helps us re-contextualize 'reactive' as finding new mechanisms for non-deformable everyday materials to find expressive ways to respond to the conditions around them - the environment, the systems

that support them, and relationships to humans. The focus is on working specifically with concrete and other cementitious materials (ceramics and plaster) because of the material permanence. Once cast or printed, the form is unchanged. However, treating them with thermochromic inks enables actuation without deformation. This research focuses on the integration of material (characteristics of thermal diffusion, surface effects) and technical features embedding intelligent systems to activate and control responses. Formal characteristics of these surfaces are rooted in passive management of heat patterns and in passive cooling based on convection. Building upon our previous research on thermal actuation through surface geometry and figuration, the form-making is meant to be tightly coupled with expression of color and perception of temperature (*Image 2*).

A common problem within shared workspaces is the thermal comfort and thermal preferences of building occupants. Many previous studies prove that the perception of thermal gradients is hard to average for engineering solutions, as these are conditioned by differences in gender, race, and culture.⁹ Two different people from two different contexts may perceive the same thermal condition in extremely diverse ways. Uniformity of current mechanical systems in buildings does not allow for individualized feedback. We focus on fostering the positive relationships between individual thermal comfort, energy usage, color, and human perception. With new thermally actuated materials there is potential to provide individualized thermoregulation, effect large scale energy savings through adaptive thermal comfort, impact human health, and reduce mechanical system loads in buildings. Our solution not only allows for thermochromic effects to be produced but adapts microclimates on the surface of the concrete panels. This in turn radiates heat into the surrounding area. Unlike current HVAC systems, which uniformly direct conditioned air to large areas of buildings, our proposed research can be adapted to panelized systems with the ability to actuate the thermal conditions in highly localized areas through use of radiant heat. The larger application of sense-based radiant heat actuation would be a transformative technology for architecture and engineering and have a positive effect on human perception and individualized thermal comfort. As such, we can imagine that with thermally-reactive, modular, and programmable architecture, a co-working space could be configured to the individual preferences of each person in the space.

9 Karjalainen, Sami. 2012. "Thermal comfort and gender: a literature review." *Indoor Air* 22, no. 2: 96 – 109.

Background and Related Work

- 10 Weiser, Mark. 1991. "The Computer for the 21st Century." *Scientific American* 269 no. 3: 94–104.
- 11 Atzori, Luigi, Antonio Iera and Giacomo Morabito. 2010. "The Internet of Things: A Survey" *Computer Networks* 54 no. 15: doi:10.1016/j.comnet.2010.05.010
- 12 Perera, Charith, Chi Harold Liu and Simal Jayawardena. 2015. "The Emerging Internet of Things Marketplace From an Industrial Perspective: A Survey." *IEEE Transactions on Emerging Topics in Computing* 3 no.4: 585–598.
- 13 Yang, Rayoung and Mark W. Newman. 2012. "Learning from a Learning Thermostat: Lessons for Intelligent Systems for the Home." In *UbiComp 2013 Proceedings*, Zurich, September 2013. 93–102.
- 14 Schellen, Lisje and Joost van Hoof. (2016). "Thermal Comfort in Smart Homes for an Aging Population." In *Handbook of Smart Homes*. Eds. Joost van Hoof, George Demiris and Eveline Wouters. 475–484. New York: Springer International Publishing
- 15 Picon, Antoine. 2015. *Smart cities: A Spatialised Intelligence*. Hoboken: Wiley. 1), 32–37.
- 16 Lee, Ming Kyung, Jodi Forlizzi, Junsung Kim and Sara Kiesler, S. 2015. "Personalization Revisited: A Reflective Approach Helps People Better Personalize Health Services and Motivates Them to Increase Physical Activity." In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, Japan, 2015. 743–754. ACM
- 17 Krueger, Myron W. 1977. "Responsive Environments." In *AFIPS '77 Proceedings of the June 13-16, 1977, National Computer Conference*, Wisconsin 1977. 423–433. ACM.

Ubiquitous Computing: In 1991, Weiser suggested that our homes and buildings would soon be made intelligent by embedding hundreds of interconnected computers in a single room.¹⁰ Today, and owing to extensive efforts in networking and computation - spanning distributed networks, context-aware computing, sensing and monitoring, analytics, prediction, and more - this vision of ubiquitous computing is largely realized.¹¹ This has created emerging markets and consumer adoption for smart objects like lightbulbs, sockets or thermostats¹² that now augment building infrastructure in our homes and workplaces. These connected devices have been demonstrated to improve the thermal comfort¹³ and occupant health.¹⁴ As such, ubicomp plays an increasingly important role in today's built environment. Yet, it rarely intersects with the architecture of the spaces it influences: it is rarely embedded in its infrastructure, rarely interacts with building systems (HVAC, etc.), nor do they employ deep integration with architectural forms. Scholars like Picon¹⁵ recognize that this is insufficient and highlight how truly embedded systems could significantly enhance the experience and interactions with physical infrastructure.

Smart and Responsive Environments: Another critique relates to how ubiquitous computing currently responds to human occupants. Lee et al¹⁶ note that "current approaches to personalization either presuppose people's needs and automatically tailor services or provide formulaic options for people to customize." Instead of forming mutually enriching, reciprocal relationships, ubicomp typically provides shallow forms of personalization. To this end, we consider Krueger's definition of 'responsive environments' where "experience is controlled by a composition which anticipates the participant's actions and flirts with his expectations."¹⁷ Krueger proposed a new aesthetic framework where sensing and computation leverage rich context, like body, pose, proximity, and other forms of context to drive intelligent, real-time responses to human behavior with applications within and beyond aesthetic expression, such as psychology and psychotherapy. These are of particular relevance to our work. Despite Krueger's assertion that responsive, context-aware technology will learn to 'perceive our behavior' and 'enter every home and office,' it has largely failed to do so. Explorations of this framework have been limited to media arts frameworks for performance or to demonstrator platforms. In media arts this is often a vehicle to explore

new performer-machine relationships. For example *Pathfinder*¹⁸, a choreographic research project, combines generative visual prompts projected in performance spaces to guide man-machine improvisation, while *Breath: between two bodies*¹⁹ leverages physiological measures from performers to generate movement vocabularies generating introspective response to sensed information.

These performative efforts are highly attuned to the ways in which sensing and context awareness can provide insight on and respond to human behavior. The relationships, however, operate in highly specialized contexts where movement grammars and behaviors are well defined. Smart space demonstrators aim to respond to more generalized scenarios. Efforts like MIT's House-n and Georgia Tech's Aware Home try to simulate smart home concepts and demonstrate the potential of responsive systems in everyday life. Favoring functional improvement of the home (reducing energy consumption, increasing efficiency, etc.), here sensing is typically situated on more measurable scenarios i.e. appliance use, temperature, etc.²⁰ Some efforts do incorporate occupant biometrics and context; normally temperature does adapt to interior conditions.²¹ However, owing to the technical challenges in generalized environments²², biometrics are rarely gathered and typically with limited scope. This results in the human occupant being treated as a secondary source. Consequently, smart home explorations rarely approach the aesthetic or experiential personalization that new media installations or performance does. Furthermore, Takayama et al.²³ note the limitations of most simulated smart home deployments; they are excellent tools for exploring issues of usability, but they are not suited to investigating interaction in the long term and fail to simulate the true conditions, practices, behaviors, and attachments which may be observed in real spaces, for example, "the stresses of hectic work and social lives." Our work responds to this, and we aim to re-engage Kreuger's²⁴ framework in applied settings. Acknowledging this critique of smart space explorations, we aim to prioritize understanding of human behavior to adapt interior spaces towards human benefit.

Responsive Environments and Smart Materials: As part of Kreuger's framework the space must intelligently respond to occupants, as well as *flirting with their expectations*. Yet, responsive architecture has for over 30 years leveraged the same material interactions: overlaid projections, programmable lighting, and mechanical actuation.²⁵ Recent developments in new programmable materials open up new avenues for unexpected responses. For

18 Pathfinder. generative computing and conceptual choreography by Onformative in collaboration with Christian Loclair. 2015. Retrieved from: <https://onformative.com/work/pathfinder>

19 Schiphorst, Thecla and Kristina Andersen. 2004. "Between Bodies: using Experience Modeling to Create Gestural Protocols for Physiological Data Transfer." In *altCHI, CHI 2004, CHI Vienna*, 2014. 1 – 8.

20 Helal, Sumi, William Mann, Hicham El-Zabadani, Jeffery King, Youssef Kaddoura, and Erwin Jansen. 2005. "The Gator Tech Smart House: A Programmable Pervasive Space." *Compute* 38 no. 3: 50 – 60. IEEE Computer Society Press

21 Helal, Sumi, William Mann, Hicham El-Zabadani, Jeffery King, Youssef Kaddoura, and Erwin Jansen. 2005. "The Gator Tech Smart House: A Programmable Pervasive Space." *Compute* 38 no. 3: 50 – 60. IEEE Computer Society Press

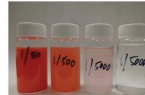
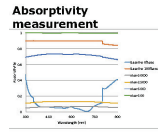
22 Tistarelli, Massimo, Stan Z. Li, and Rama Chellappa, eds. 2009. *Handbook of Remote Biometrics*. New York: Springer International Publishing.

23 Takayama, Leila, Caroline Pantofaru, David Robson, Bianca Soto and Michael Barry. 2012. "Making technology homey: finding sources of satisfaction and meaning in home automation." In *UbiComp '12 Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, Pittsburg, 2012. 511 – 520. ACM.

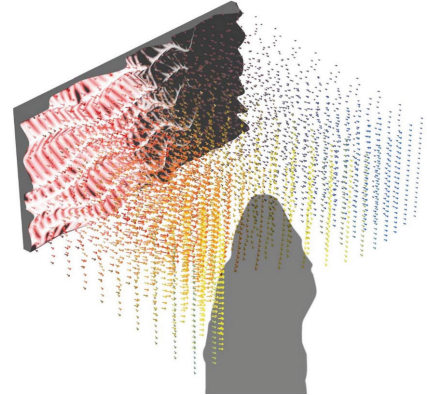
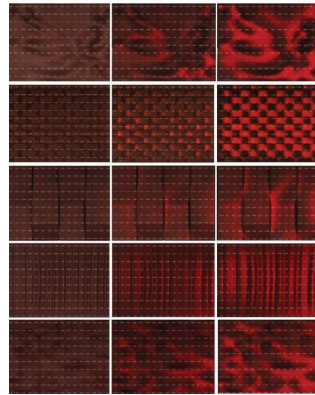
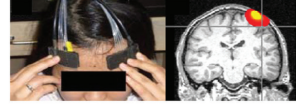
24 Krueger, 1977

25 Fox, 2016

Image 2 Thermally Activated Surface Color change with proposed bio-metric actuation using Nirs Biofeedback: Tests of thermo-chromic progression of varied surface geometry associating the color change and temperature values to surface geometry variation (Cupkova, 2016). We can activate the surface temperature by sensing human presence and link the visual effects on the surface to an emotive human response, thus creating new form of communication between the environment and the human perception of thermal and physiological comfort. Example of optical probes placed on subject's forehead (top right). The area of the brain probed is shown on the right overlapped on a MRI brain image (Kainerstorfer, 2014).



NIRS]BIOFEEDBACK

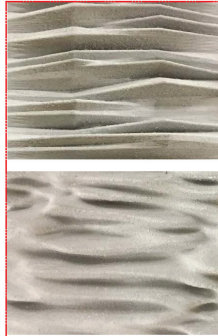


- 26 Devendorf, Laura, et al. 2016. "I don't want to wear a screen: Probing Perceptions of and Possibilities for Dynamic Displays on Clothing." In CHI '16 - Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, New York, 2016. 6028 – 6039. ACM.
- 27 Berzowska, Joanna. 2004. "Very slowly animating textiles: shimmering flower." In SIGGRAPH 2004 Sketches, Los Angeles, 2004. 34. ACM.
- 28 Yao, L., Niyama, R., Ou, J., Follmer, S., Della Silva, C., & Ishii, H. (2013). "PneUI: pneumatically actuated soft composite materials for shape changing interfaces." In UIST '13 Proceedings of the 26th annual ACM symposium on User interface software and technology, United Kingdom, 2013. 13 – 22. ACM.
- 29 Addington, D. Michelle, and Daniel Schodek. 2012. Smart Materials & Technologies in Architecture. Burlington: Routledge.
- 30 Robles, Erica and Mikael Wiberg. 2011. "From Materials to Materiality: Thinking of Computation from within an Icehotel." Interactions 18 no. 1: 32 – 37.

example, Devendorf et al.²⁶ explore computationally responsive clothing that create chromic responses as a novel textile display technology. Berzowska²⁷ similarly explores conductive yarns and thermochromic inks blended with electronic components to create dynamic fabrics, while Yao et al.²⁸ have explored pneumatic shape-changing systems and biological methods to deform soft materials through environmental changes. Due to their materiality, they also have the potential to be more deeply coupled with architectural forms and truly embed computation into the space it is designed to actuate²⁹ but - like work in ubicomp - almost all of this work focuses on small, object level interventions, and the potential of these materials to operate at an architectural scale remains unexplored. Robles and Wiberg³⁰ note the need to interface with computation at scale and through new materials as well as integrative design-led inquiry into these emerging areas:

"With the development of rapid prototyping processes, inexpensive chips, processors, and sensors, and increasingly computational ways of interacting with manufacturing and craft processes, our relationships to materials are rapidly transforming... Open for examination is how the discipline of interaction design might move forward alongside architecture, product design, textile design, and materials science as part of a joint area for inquiry."

SURFACE MORPHOLOGY:
The geometric articulation of the surface area actively affects thermal behavior.



We know, from our previous research (Cupkova et al.), that we have the ability to strategically delay heat re-radiation of 35°C by 75 minutes within 3 hours, just through the figuring of mass to surface related to solar geometry.

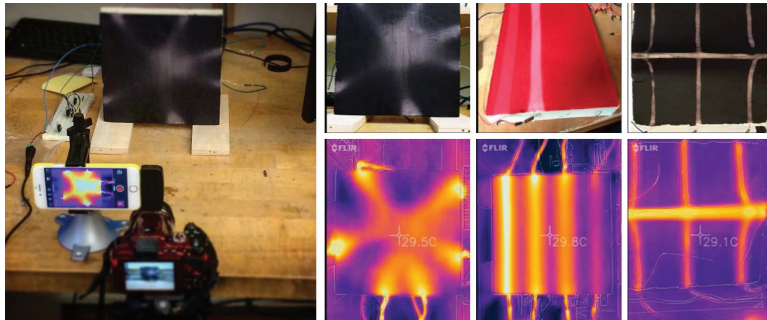
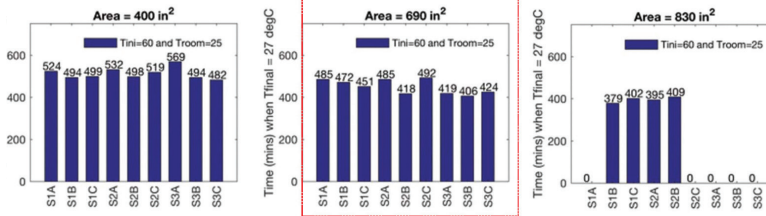


Image 3 The geometric articulation of the surface area actively affects thermal behavior: We know, from our previous research (Cupkova et al.), that we have the ability to strategically delay heat re-radiation of 35°C by 75 minutes within 3 hours, just through the figuring of mass to surface related to solar geometry. This paper explores combining active and passive systems and features test panels with embedded thermal network testing range of activation: location and depth showing the interaction of surface geometry with chromic pigments and thermal control through electromechanical actuation.

Contextualizing Work to Date

In response to Robles' and Wiberg's call to action, our preliminary work (*Image 3*) recognizes the need for arts-based exploration of new material interactivity. Our prior work explores an alternative approach to the architectural design of passive building systems, actuating passive thermoregulation through the use of surface geometry, material, and color. This ongoing research outlines principles for the design of passive systems with a creative approach towards performance and form. It is built upon the premise that complex geometries can be used to improve both the aesthetic and

31 Cupkova and Promoppatum, 2017.

thermodynamic performance of passive building systems by actuating thermal performance through geometric surface figuration that is responsive to localized color change, primarily due to convection.³¹ We measured up to 45% possible reduction in energy usage if these strategies are used. This phenomenon is primarily caused by the fact that specific types of surface geometry tend to reduce direct surface contact between airflow and wall surface area by creating air pockets, thus generating differences in thermal performance and perception.

32 Cupkova, Byrne and Cascaval, 2018.

Sentient Concrete prototype extends these prior explorations and developed a reactive concrete panel prototype with embedded electromechanical controls. This panel can be programmed to actuate internal thermal changes and produce color effects on the surface.³² This enables surface thermal, tactile, and thermochromic responses to be reliably actuated in under 1 second. This produces highly reactive character changes in the surface conditions that can be coupled to a variety of human responses and behaviors; in this case, proximity and brain activity were explored. This small-scale panel provides a proof-of-concept of the ability to create responsive, reciprocal interactions between human physiology and smart materials central to this research proposal. To achieve intended goals, these panels need to move beyond small scale tests and laboratory settings.

33 Kainerstorfer, Jana M., Angelo Sassaroli and Sergio Fantini. 2014. "Coherent Hemodynamics Spectroscopy in a Single Step." *Biomedical Optics Express* 5 no.10: 3403 – 3416.

Accordingly, this will require the development of immersive interactive architectural experiences that respond to human behavior. Insights in producing this real-time emergent responsive system will directly inform the development of this work. The intention is to integrate multiple sensed sources from human participants in ecologically valid conditions and combine design technology approach with neuroscientific feedback within CMU collaborative context, by using non-invasive optical or NIRS techniques: near-infrared light at two different wavelengths is transmitted through the intact scalp and skull to illuminate the brain.³³ An optical fiber is placed in a specific scalp location to deliver an optical signal, while a separate optical fiber, typically placed a couple of centimeters away from the illumination point, collects the light that has probed the cerebral tissue. This optical method can be used to assess changes in tissue perfusion and oxygenation. Positive changes in tissue perfusion and oxygenation are associated with demand, which is seen in functional brain activation. For example, NIRS optical probes can be applied to the motor cortex to reliably detect activities such as finger tapping. In addition to functional activations, Kainerstorfer's work has demonstrated

NIRS is sensitive to systemic physiological changes, for instance triggered by changes in mean arterial blood pressure. Those changes include heart beat fluctuations in hemoglobin and respiration.³⁴ We hypothesize this will allow us to monitor hemodynamic changes in subjects and correlate them to changes and responses in the environment.

34 Kainerstorfer, Sassaroli, and Fantini, 2014.

Projection

This framework is motivated by the belief that today's architectural spaces and systems are insufficient. We hypothesize that our built environment can support healthier relationships with its human occupants if it can understand and respond to them intuitively. To address the limitations of today's environments, our research shall explore reciprocal relationships between mind, body, and space that can be developed with thermally and visually responsive architectural materials:

Mind: Leveraging NIRS signals, we assert that we can measure attention, functional activations in the brain, as well as changes in heart rate and respiration that may indicate stress, affect, and mood. Furthermore, we assert that we can leverage these as inputs to meaningfully augment the environment for a building occupant.

Body: We assert that human somatic behaviors and thermal signatures can be used to improve the personalization and adaptation of the space to each occupant. We assert that knowledge of each individual's location in space, orientation, environmental context, and thermal profile can be used to personalize the aesthetic and thermal conditions of a space.

Space: We assert that psychosomatic knowledge of building occupants will allow reactive architecture to affect thermal and visual change to positively affect health and wellbeing.

To methodologically ground our design-based research process, we will draw on and extend Krueger's³⁵ framework for responsive environments. Our research framework will therefore a) develop new psychosomatic concrete panel prototypes and fabrication techniques to support their production; b) examine the sensing, control, and coordination that allows human biometrics, behavior, and response to be reliably gathered as inputs to our

35 Krueger, 1977

architectural system; c) interrogate and design strategies to affect human response through thermal and aesthetic changes in their surrounding; and d) evaluate and assess the degree to which this can affect and impact human wellbeing in the short and long term.

This proposition extends directly to the design of environments by inciting thermal fields as active spaces that are attuned to the human psyche. Just like a “mood ring,” this thermally reactive architecture would renegotiate a sense of individual and collective reflections in lieu of a singular spatial (and thermal) norm that represents an average measurement. Instead we propose a functionality that attempts to produce spaces that respond to human diversity. Attunement in this regard requires a shift away from the data-driven rationales of performative models and the desire for design to tap into architectural sensorial subjectivity as part of the aesthetic and ecological experience.

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