Environment-Responsive Materials as Dynamic Markers for Architectural Augmented Reality Applications

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With growing knowledge of our environmental obligations, architects must explore new design techniques and find alternative strategies to express environmental aspects in architecture. Augmented Reality (AR) is a digital technology that allows us to enhance a real data feed with digital data virtually and is becoming ever more ubiquitous. It is widely used in industrial environments and is still novel in architecture, and has only recently gained popularity. The use of marker-based AR in dynamic, non-standardised architectural spaces is limited. Nevertheless, the technology can potentially help visualise thermal conditions invisible to the human eye. The paper presents a detailed state-of-the-art review of AR and thermochromic materials in architecture. From this, it derives a series of relationships between the two technologies. They are explored through design experiments and prototyping. The research reconsiders digital design parameters in this context, yet, the scalability of results remains a future task.

Keywords: *Augmented Reality, Thermochromic Materials, Digital Fabrication, Environmental Simulations.*

INTRODUCTION

With increasing awareness of our environmental responsibilities, architects must engage with alternative solutions to communicate invisible environmental parameters of thermal comfort, requiring new design tools to communicate such qualities of space actively. This research investigates a very low-tech and high-impact design method that incorporates environmental considerations into morphological processes for geometries that are detectable by Augmented Reality (AR) applications. The results are postdigital prototypes that operate on the thresholds of materials, environments, and digital technology.

Using thermochromic materials in complex architectural spaces allows for performative and aesthetic communication of thermal comfort parameters without digital links, increasing cross-platform compatibility. Architects can design visually appealing effects that resonate with humans, granting them agency in a streamlined built environment.

AR

AR is a phygital technology that allows us to enhance a real data feed with digital data virtually. As an emergent technology, AR is becoming ever more ubiquitous. There is static and mobile data processing, where the latter move with the user, such as hand-held devices like smartphones and tablets or head-mounted displays like *Microsoft HoloLens* (Russo 2021). Especially the focus of large firms on online shopping has driven the development of AR applications for use in everyday life. In e-commerce today, various retailers integrate AR into the online sales process, like *L'Oréal* with its virtual mirror. According to *Apple,* AR is a game-changer (Đurđević et al 2019). Inbuilt apps like *Measure* and the LiDar sensors on the new *iPhone* and *iPad Pro* series reflect *Apple's* trust in the technology.

AR in art, design, and architecture

In the arts, AR is used more frequently in exhibition setups to increase the interactivity and gamification of museum spaces. Many artists engage with AR—apps like *Artivive* overlay paintings with virtual content on mobile devices. In an interior context, hands-on apps like *IKEA Place* introduced a simple version of AR to the broader public. However, AR is mainly used as a representative tool within architecture and urban planning. For example, showcasing reconstructions of cultural heritage (Blanco-Pons et al 2019), during construction via BIM-informed systems, for customer visualisation, in education, or with LiDar scanners, e.g., *Apple's API RoomPlan*. Much research concerns enhancing fabrication and construction, like the work by various researchers using *Fologram*'s *Grasshopper* interface for *Hololens (*Newham et al 2023*)*. Based on this review, AR's artistic use in the digital design process remains a novel territory.

Tracking and registration processes

The setup of an AR application in the architectural realm depends on the chosen device, the tracking and registration method, and the interface establishing the hybridisation of real and virtual data. For proper alignment of virtual content into the user's viewpoint – **registration** - the physical environment is captured in real-time - **tracking** (Russo 2021). Vision-based approaches use standard or infrared cameras. Non-vision-based methods are location or position-based using GPS or a digital compass, sensor-based, and hybrid approaches (Grimm et al 2014). In recently popular vision-based approaches, cameras record physical objects to determine their relative position and orientation to the tracker (Dörner et al. 2014). After calibration, a camera frequently updates the initial reference system to changes (Russo 2021). There are outside-in and inside-out processes depending on the use of single or multiple cameras and their positioning. In the latter, the tracker estimates its position in space while moving within the interaction area. (Dörner et al 2014). Vision-based tracking works either marker-based or markerless. Markerless methods recognise specific 'natural' shapes or general geometric features in the scene, e.g., by class recognition, for position estimation (Russo 2021). Marker-based approaches rely mostly on 2d features of distinct 'artificially designed' physical markings inherent to the data of the AR (Mehler-Bicher, Steiger 2022). In architecture, research on tracking 3d-scanned spaces has intensified recently.

Passive and dynamic markers

Passive and active markers are mostly fiducial (Syed et al 2023). Fiducial applies here to the use of reference lines or points for tracking. These can be quick-response codes, barcodes, image-based, or even mixtures of barcodes and images. The printed versions of these markings are generally referred to as passive markers. They are visible to a standard camera and the human eye. Contrary, active markers use diodes that periodically emit infrared light and are only visible to IR cameras when active. The first type is much more common but has limitations. As named by Russo, there are challenges and knowledge gaps that make the use of passive markers in architectural setups complex: their spatial positioning (also concerning registration), their preservation (especially outdoors) and changing lighting situations (Russo 2021).

Nonetheless, passive, artificially designed markers are potentially relevant to architecture in the form of surface articulations. A translation from, e.g. printed QR-codes to architectural elements would be less disruptive for any architectural design. The dynamic lightning situation, however, remains a challenge.

Thermochromic materials in architecture

Smart materials can contain information (Kretzer 2017), meaning they have embedded functions usually triggered by environmental stimuli. According to Addington and Schodek (2005, p. 10), to classify materials, composites, or systems as 'smart', they must fulfil the criteria of immediacy, transiency, self-actuation, selectivity, and directness. Such smart or information materials are widely used in fashion, engineering, healthcare, and electronics. Although literature and research on smart materials in architecture exist, their application is still rare. A sub-category of smart materials is thermochromic materials or thermochromics. Thermochromism describes the change of colour due to temperature; thermotropism is the equivalent change of transparency (Seeboth and Lötzsch 2013). Since the 1960s, thermochromic materials have been explored as material-based and non-electric display alternatives (Day 1963; Grafstein et al 1968).

In the context of recent architectural research, thermochromics have been explored as methods to visualise thermal mass (Cupkova et al 2018), as pedagogic methods to visualise building performance (Burry et al 2013), and to understand the relationship between heat transfer and hollow architectural elements. The use of thermochromics as a *dynamic ornament* has been intensively researched by Mark Meagher (2010; 2013; van der Maas et al 2009). In many cases, the thermochromic effect is triggered by active, often electric, means such as e. g., heating wires. While the research presented in this paper focuses on using thermochromic markers and their design, it aims for passive and environmentally-induced temperature changes.

In buildings, thermochromic products have been developed as additives to renders, concrete mixes, and smart glazing, which changes opacity due to heat. Their promise lies in the ability to change colour due to heat which could help manage the albedo of buildings and therefore modulate heat solar heat gains. Thermochromic materials' main limitation in architecture is lightfastness. (Figure 1) Lightfastness describes a material's resistance to UV light. Therefore, external applications of thermochromics on facades have not yet been successfully implemented. Consequently, the research in this paper focuses on interior applications.

Nonetheless, thermochromic materials respond predictably to temperature changes in interiors. This property can be used as the design momentum of passive markers, which become active markers differently.

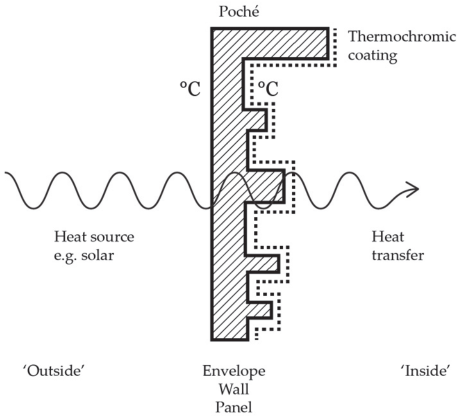


Figure 1
Thermochromics, lightfastness, and substrate relationships.

Environmental markers

Thermochromic materials have already been explored as dynamic inputs for AR applications in the context of intelligent food packaging systems. The use of smart materials has a long history in this field and sometimes goes hand in hand with the development of AR applications, as shown by the research of Đurđević et al (2019). The researchers used thermochromic inks, reacting to changes in the surface temperature of a product, as input for a dynamic AR application reacting to the maker's colour change. This provides buyers with information about the condition of food through smart labels or dyes. An artistic approach for the design of dynamic markers is the research project *dmarkers* by Peiris et al (2011). It uses thermochromics and semiconductor elements to develop subtly changing, animated displays for paper and fabric markers. The key factor was the ability to animate the material without needing a separate display. Therefore, these markers are dynamic in that they only become visible to AR at a certain time. (Figure 2) This potential has not yet been exploited for use in an architectural context, therefor this paper attempts to translate knowledge.

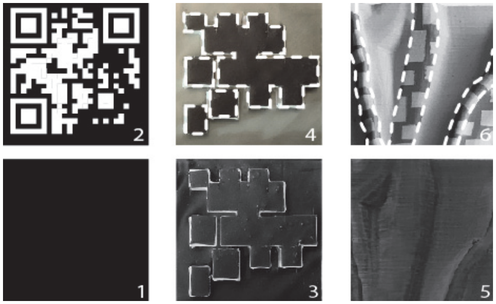


Figure 2
Principles of thermochromic, dynamic (smart) markers after (Đurđević et al, 2019).

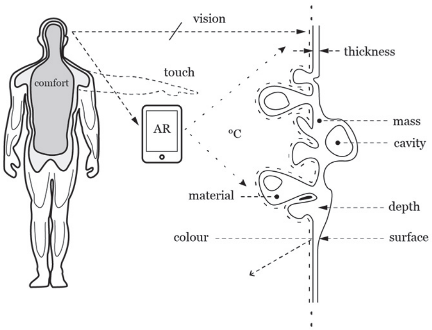


Figure 3
Relationships of AR and architectural surfaces in the context of environmental interaction.

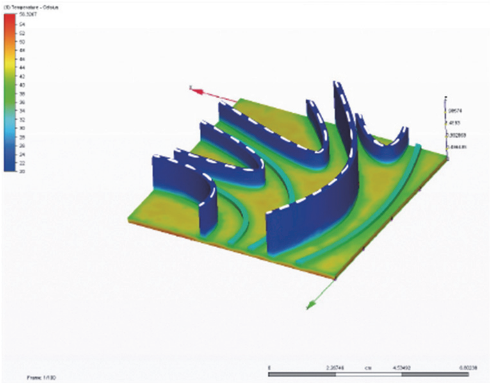
METHODS, PROCESS, AND CHALLENGES

This research investigates a design methodology for environmentally responsive markers by merging two topics, AR and thermochromics, to form a **new tool**. (Figure 3) The iterative design process consists of diverse techniques and methods. It investigates using environment-responsive materials as dynamic markers for architectural AR applications. The **scope** was limited by available resources, mainly applying to tests concerning the architectural scale. Scaling AR applications up involves many challenges, such as the size of prototypes, the distances over which the AR application must work, and the unpredictability of diverse users and environmental conditions. The authors have decided to compartmentalise the work into two categories to tackle this. A) The development of thermochromic AR markers on a smaller scale is intended to create an **understanding** of the fundamental processes and technologies. B) The fabrication of 3d prototypes using tools such as tabletop 3d-printers, off-shelf thermochromic pigments, and easy-to-use analysis tools is intended to **develop** a design method that incorporates the patterns into the topography and topology of architectural surfaces, rather than applying them. To **contextualise** the work within the wider discourse on reconsidering digital design, the authors **evaluated** potential applications in architecture. From this, three **research questions** were derived: What are the principles of designing thermochromic AR markers? How can we develop those principles into a design method for architectural surfaces? What are the potential applications and challenges for such dynamic AR markers in architecture?

Digital design and simulations

Digital design and simulations were used to develop a method to incorporate environmental considerations into morphological processes. The authors used a combination of heat transfer simulations and procedural design to generate a base geometry with many variations. Heat transfer describes the energy flow due to temperature differences within a medium or between media (Ghoshdastidar 2004). The resulting patterns were transformed and acted as the input for a series of displacement transformations. The resulting geometry was cut into smaller, square elements with distinctive topographic features. They were analysed using heat transfer simulations in *Autodesk CFD.* (Figure 4) For faster results during the design process, the simulations were substituted with a surrogate: An inverted Ambient Occlusion display mode in *Maxon Cinema 4D* to mimic the colour change according to variations in thickness. *Rhino3d* acted as a pipeline for the digital design, simulation, and fabrication process.

Figure 4
Heat transfer simulation.



Topographical marker design

The topographical marker design was explored along two methodological paths: printing, spraying, stamping, stencilling, or drawing patterns onto 3d-printed geometries. In this case, the patterns are projected onto the surface, disregarding the substrate's geometry. Second, through markers that result from the distinctive heat transfer patterns of the geometry. In this case, the pattern is innate to the substrate geometry. Concerning the AR setup, static processing of data (*Unity, Vuforia*) and mobile processing (*Samsung* tablet) were evaluated. The tracking and registration process is based on standard camera inputs of a webcam and the tablet's proprietary camera. The data fed to AR for marker matching is fiducial using reference points extracted from either patterns or geometry. The two paths were explored in three workflows:

2d to 3d. These initial tests cover rectangular patterns made of thermochromic foil on paper in black and white. When stimulated, the black base layer turns white, and the trackable marker appears, equalling the data fed to the AR. The 2d pattern was then extruded to create a 3d marker. The different heights between the multiple coated tops of the geometry allowed for multiple marker patterns, sequentially triggering AR. However, there is the risk that the AR confuses individual patterns if they are not distinct enough.

Overlays. Prototypes based on heat-transfer simulation were evaluated on their 'natural' features and tracking capacities. Other 2d patterns enhanced the trackability where necessary, mostly disregarding the substrate's topography and increasing readability for AR. Multiple layers of active (thermochromic) coatings and passive (acrylic) spray paint were used, and multiple predefined patterns were used as keyframes. Coatings are paints that protect a substrate or perform else beyond aesthetics. (Figure 5)

Topographic. A large panel structure was designed consisting of 108 individual elements assembled in two rectangular grids of 6x9 elements. Each element is distinctively different, but the degree of difference varies across the panel. A selection of elements was made based on maximum variation to explore different patterns. The elements were printed with a uniform thickness, proving to work well for heat transfer and printing speed but inadequate for exploring variations in thermal mass. Therefore, the experiments were limited to topographic investigations of the surfaces.

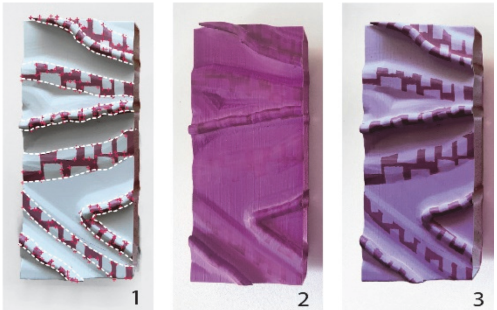


Figure 5
Thermochromic overlay and pattern.
1) Base pattern without thermochromic coating. 2) Cold thermochromic marker. 3) Hot thermochromic marker.

Fabrication

For the prototypes, fused deposition 3d printing with PLA was used. After a series of idiosyncratic studies for initial testing, a larger assembly of 108 parts were fabricated. Each part was coated using thermochromic ink that changed from purple to white at 27 °C.

Material and geometry tests. A series of base geometries were 3d-printed and coated with various marker patterns and coating methods. Those studies helped identify key design parameters for 3d, environmentally dynamic marker patterns recognisable for AR. The patterns ranged from pixelated (sharp features) to striated (barcodes) and the filling of larger areas (silhouettes), done conjointly with the development of AR.

Assembled prototype. An assembly of two panels was designed to explore a larger scale while committing to small-scale elements. This thermochromic screen consists of parts with distinctive geometric features. When warming up, distinctive patterns emerge, acting as geometry-innate dynamic markers. In this case, all parts were coated with a continuous film of purple thermochromic ink. The prototype was then preliminarily tested during an event at the faculty.

RESULTS

The research yielded two sets of results. One is a library of prototypes that document a variety of explorations. They include key findings concerning marker design, patterns, the use of thermochromics, and fabrication. The other one is the assembly, including findings concerning future applications, potential pitfalls, and limitations for use on an architectural scale.

Environmentally dynamic markers

Geometry-innate heat patterns are suitable as a data reference set for generating fiducial, environmentally-responsive markers. (Figure 6) When registration requires data matching, the reference set must be simulated in advance, and the promising potential of unknown intermediate steps cannot be exploited. This is a task for the future. Nevertheless, some important parameters for enhancing tracking efficiency were defined:

- High contrast between foreground and background colours is required.
- Further spacing between valleys and high points is more beneficial.
- Heat transfer simulations can help to animate patterns like keyframes for dynamic markers.
- The angle at which the marker is viewed is relevant.

Architectural screen

The assembly provides a large variety of distinctive patterns. (Figure 7) The precise actuation of each element proves challenging since it must rely on an active, localised heating system or precise knowledge of the ambient environment. The developed screen relies on applying heat through a device, e.g. a hairdryer, or human interaction through touch or breath. In the assembly case, the 2d patterns were spatialised as 3d elements that, together with the thermochromic animation, create a 4d screen.

DISCUSSION

When reviewing the results, a series of observations can be made concerning the viability of this method to design dynamic, thermochromic markers for AR applications in architecture. (Figure 8)

Critical reflections

The heating system is not yet clearly defined. When moving from basic to applied research, it is important to identify ways to control the effect (Stokes 1997). In the future, it would be beneficial to use combined visual tracking techniques, e.g., by adding a thermal imaging camera for AR. Further, it looks promising to deviate from patterns, image-based, and marker-based to colour or hue and saturation-based approaches for certain applications. Based on the results, using geometry-innate features and designed thermal mass for marker patterns appears feasible and promising. So far, the research has been conducted without a clear used case and a concrete concept of the information shown via AR. Again, specific applications such as passive temperature sensors in inaccessible spaces appear as promising technology applications. After

Figure 6
Dynamic, fiducial markers and tracking (yellow crosses).

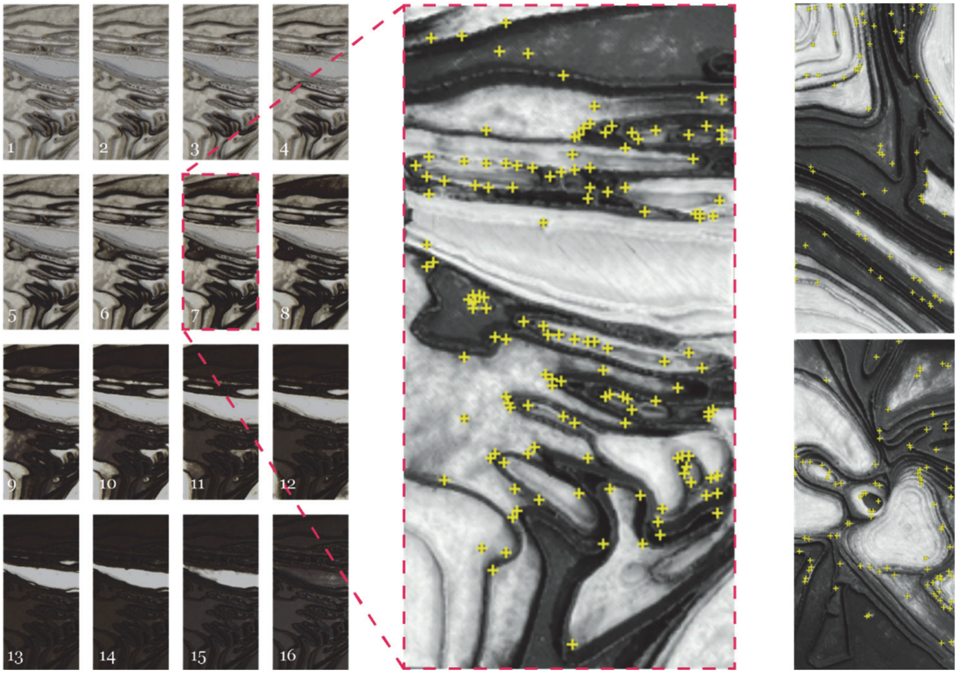
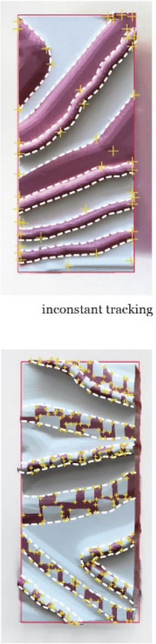


Figure 7
Architectural screen with characteristic patterns (white) when exposed to temperatures above 27°C.



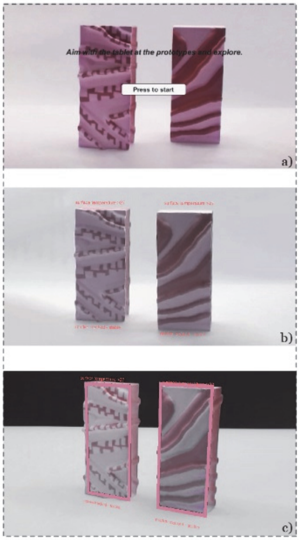


Figure 8
AR overlays and patterns. a) Position check, b) Tracked marker, c) Initial interface

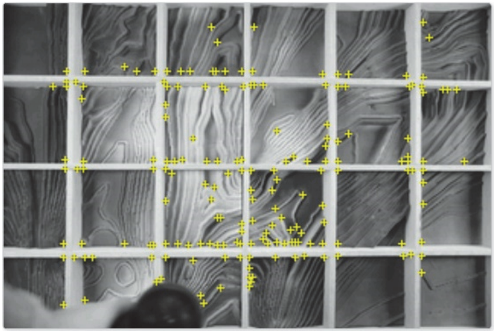


Figure 10
AR features were analysed with Vuforia Target Manager. The yellow crosses mark successful tracking. Currently, the frame is too dominant and disrupts tracking. (Vuforia tracks only in greyscale.)

reviewing the results, the authors question whether the direct use of infrared cameras has much potential. (Figure 9) This approach would allow the omission of the thermochromic pigments and would work solemnly with heat patterns. The downside would be that there is no otherwise visual effect perceptible by humans, which is key to the research.

Limitations and future studies

More research on the technology on an architectural scale is needed. Computational aspects of mobile devices, tracking distances, prototype dimensions, and economics must be considered before making premature conclusions concerning the feasibility of environment-responsive materials as dynamic markers for architectural augmented reality applications. Thermochromic materials are expensive and often toxic, but organic synthesis is already being investigated (Seeboth et al 2013). This would make working with such materials safer and more ecological. The issue of lightfastness must not be ignored for any architectural application on exterior surfaces. Modulating thermal mass, as in the case of Cuokova et al (2017), and transmitting heat from outside to inside (if tolerated) appears a promising path forward. The issue of tracking stability concerning changing light conditions must be resolved. In the assembly of parts, the subdividing grid is currently far too dominant.

Consequently, this disrupts the recognition of thermochromic patterns. Future studies must consider the design of the sub-structure and part division more carefully. (Figure 10)

Potential applications in architecture

The research investigated fundamentals in designing dynamic markers with thermochromic materials in architecture. This low-tech and high-

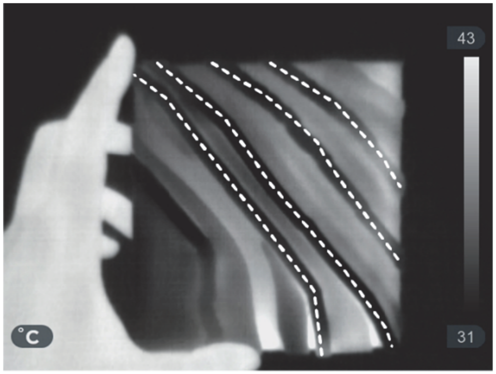


Figure 9
Using infrared thermography as an input.

might seem redundant, the authors have identified some promising architectural benefits based on this analogue-digital feedback setup. Compared to impact method can be adapted for several uses for hybrid environments in architecture. While the setup electronic sensors and displays, a setup of thermochromics and AR operates with an established construction method (coating) and an emergent digital method (AR). For example, the AR application signals an event once a certain surface temperature is reached, which can be anticipated via heat transfer simulations. The response, e.g., lowering blinds or opening a window, is then executed by a human, working both with and without the AR application since the signal is also visible to the naked eye depending on the design. The results are layered densities of information. It makes such applications suitable in environments where electronic solutions are not feasible due to a lack of reliable, static infrastructure. As discussed by others, this technology can also be used for navigation in buildings (van der Maas et al 2009). There it can provide information about invisible environmental conditions over greater distances.

CONCLUSION

Environment-responsive materials as novel dynamic markers for architectural augmented reality applications promise hybridisations of smart materials and digital technologies. Such environmentally-informed mixed reality environments show great potential for further development in the context of architecture. AR technologies are advancing at an accelerating pace and will become part of the architectural repertoire. While the possibilities of what content is overlaid are endless, some conclusive remarks can be made based on the before-listed results. Using distinctive, geometry-innate heat patterns as dynamic markers appears promising. Using thermochromic materials to communicate previously invisible thermal comfort parameters in complex architectural spaces is both a performative and aesthetic effect. It requires no digital link between the device and source, increasing potential cross-platform compatibility.

Furthermore, such aesthetic effects and patterns can be designed to appeal to humans who are the ultimate users of buildings, allowing architects to gain agency in an increasingly economically and technically streamlined built environment. Ultimately this hybrid process merges physical and digital processes in a new form of postdigital augmentation, which reconsiders digital design in architecture.

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