



## RESEARCH ARTICLE

# In situ Simulation of Thermal Reality

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Simulated reality encompasses virtual, augmented, and mixed realities—each characterized by different degrees of truthfulness in the visual perception: “all false,” “coexistence of true and false,” and “difficult distinction between true and false,” respectively. In all these technologies, however, the temperature rendering of virtual objects is still an unsolved problem. Undoubtedly, the lack of thermal tactile functions substantially reduces the quality of the user’s real-experience perception. To address this challenge, we propose theoretically and realize experimentally a technological platform for the in situ simulation of thermal reality. To this purpose, we design a thermal metadvice consisting of a reconfigurable array of radiating units, capable of generating the thermal image of any virtual object, and thus rendering it in situ together with its thermal signature. This is a substantial technological advance, which opens up new possibilities for simulated reality and its applications to human activities.

## Introduction

Simulated reality [1–5], also known as immersive computing technology, provides a computer-generated digital landscape that allows users to enter and operate in a simulated environment. It proved to be a powerful tool in a variety of fields, including studio entertainment [6–8], art design [9], education [10], business [11], medical science [12], aerospace [13], and other industrial sectors [14,15]. Over the past few decades, core technologies such as video coding optimization [16], controlled rehabilitation scenarios [17], and more emerging technologies in, e.g., car driving and online meeting [18] have been increasingly applied to visually simulated reality. However, to achieve truly immersive simulated reality, visual experiences alone are not sufficient. The system must integrate various forms of sensory feedback, including crucially thermal sensing, to enhance the realism of the virtual perception. Recent advancements have underscored the potential of thermal technology in augmenting reality [19]. Nonetheless, a chasm still exists between state-of-the-art thermal technology, which holds promise for developing a deeper level of immersive entertainment, and the thermal devices currently used in augmented reality applications.

Ideally, simulated reality technology should recreate all perceptive functions of the users. Indeed, the expected success of simulated reality lies in its ability to offer comprehensive and real-time experiences, which necessarily include, besides interactive images and sounds [20–22], also the sense of touch [23–26]

and other sensations. One of the most critical tactile functions of the human sensory system is thermoception, or the ability to sense temperature, which can significantly enhance a user’s interaction with the external environment. Therefore, many attempts have been made to recreate thermal sensing. Incipiently, researchers found that thermoception is impacted by visual perceptions [27]. For example, the association of colors to different temperatures [28], for instance, red with warmth and blue with cold, can be leveraged to enhance the realism of simulated thermal experiences. Also, by connecting infrared cameras with visual displays [29,30], a thermal infrared vision is rendered for the user’s view, manipulating thermoception in virtual reality. Recently, thermal haptic technology has found its way into various industrial applications. Devices like “Thermovr” resort to Peltier devices to simulate the heating/cooling sensation [31]. “Ambiotherm” and “Season Traveller” products provide wearable thermal haptics to enhance ambient temperature [32,33], giving a realistic convective sensation. However, despite these advancements [27–35], accurately reproducing thermal perception in simulated reality remains a challenge. In particular, virtual and actual objects in simulated reality must retain their own temperature and emit thermal radiation according to the Stefan–Boltzmann law. The advances thus far have primarily addressed ex situ settings, which leaves the in situ simulation of thermal reality a still open challenge.

To address this challenge, here we develop an advanced technological platform that allows in situ thermal rendering

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of virtual objects within simulated reality environments. The proposed setting recreates thermal sensing and can be incorporated in thermal infrared vision. To illustrate this concept, we first present thermal infrared renderings of virtual, augmented, and mixed reality scenes through an example (Fig. 1). To achieve our goal, we design a metadvice capable of generating infrared patterns of arbitrary objects. As a proof of concept, we demonstrate experimentally that a variety of patterns can be generated in our reconfigurable thermal metadvice. Switching between different patterns was obtained by electrically reconfiguring the thermal metadvice in a programmable and computer-controlled manner. This work opens up a path toward unprecedented immersive experience with in situ thermal tactile sensation.

## Results

### Concept

Figure 1A summarizes the main characteristics of visual sensing in simulated realities. In virtual reality, computer-generated virtual objects are easily distinguishable from actual objects due to current imaging technology limitations. Augmented reality allows for more interaction between virtual objects and the natural environment, with virtual objects following the physical laws of the natural world. Mixed reality takes this a step further,

offering a more natural interaction between humans and virtual objects, with virtual objects responding to human actions in a real environment. However, as mentioned above, a key element still missing in the current simulated reality settings is the thermal perception of virtual objects and environments. The proposed technology of “in situ simulation of thermal realities” aims at overcoming such a limitation. We have selected specific scenarios in simulated realities to showcase the expected scenarios obtained using our technology. Figure 1B to D illustrates a scene where a user is sitting in front of a table (actual) and creates a cup of hot coffee (virtual) in her hand using a simulated reality device (Fig. 1B). She then pours the hot coffee into a kettle (actual) on the table (Fig. 1C), and the hot coffee fills the kettle (Fig. 1D). It is worth emphasizing that the creation of virtual objects in Fig. 1B, the interaction between the user and virtual objects in Fig. 1C, and the interaction between virtual objects and the natural environment in Fig. 1D exhibit the characteristics of virtual, mixed, and augmented reality, respectively. Figure 1E to G illustrates the real thermal infrared scenes of Fig. 1B to D, where virtual objects (cup and coffee) do not emit thermal radiation. Vice versa, based on the technology of “in situ simulation of thermal realities,” virtual objects (cup and coffee) do generate thermal radiation corresponding to their temperature, as shown in Fig. 1H to J.

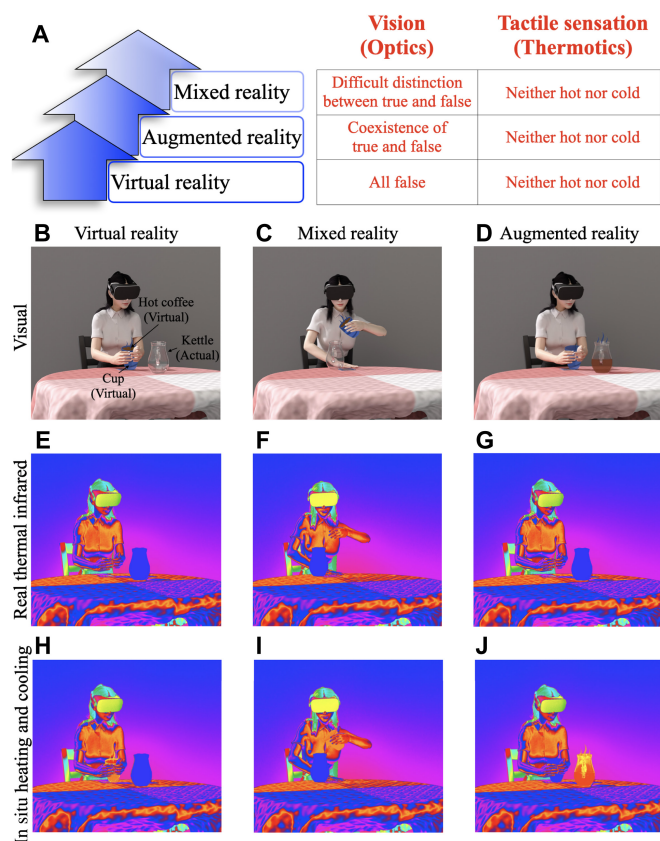
### Experimental Realization

The proposed approach to the in situ simulation of thermal realities consists of 3 steps. In the first step, a radiating metadvice is developed, based on the “thermotics” technology [36–48], capable of generating the thermal infrared pattern of an arbitrary object [49–60]. In the second step, using the existing computer rendering technology, the generated thermal signals are seamlessly associated with the virtual objects in the simulated reality scene. In the third step, the corresponding thermal tactile sensing of virtual objects is recreated in situ by means of an appropriate hardware. The present work focuses on the experimental implementation of the first step.

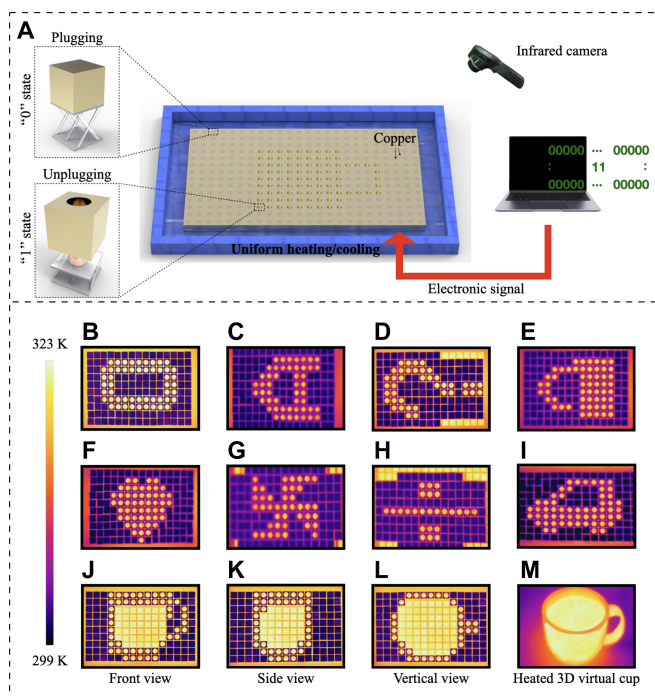
The experimental setup, sketched in Fig. 2A, consists of a metadvice in the form of a square array of programmable cubic units, placed on a uniform heat source. A computer controls electronically the plugging (“0” state) and unplugging (“1” state) of the cylinder (copper) at the center of each unit (copper), thus tuning the effective emissivity of the unit. More refined thermal patterns can be obtained by partial unplugging of the unit cylinders. We start by artificially configuring the initial state of the units targeted in the experiment. In principle, the effective thermal emissivity of the units can be independently and continuously adjusted. To create clearer thermal infrared patterns, we choose the “plugging” and “unplugging” units with the minimum and maximum emissivity, respectively. More details about the underlying theoretical mechanisms and the experimental procedures are reported in Figs. S1 and S2. As a test, we then experimentally generated the 2-dimensional (2D) thermal infrared patterns plotted in Fig. 2B to I.

### Scheme for Virtual Object Rendering

For a 3D scenario, we selected a cup as a model and generated the front, side, and vertical views of its infrared patterns shown in Fig. 2J to L. We manually merged the three 2D thermal infrared patterns (or temperature profiles) of a heated cup into the 3D view of Fig. 2M, namely, an in situ thermal image of the cup. In principle, one can develop an image processing algorithm to



**Fig. 1.** Schematic graph for heating/cooling simulated realities in situ. (A) Characteristics of visual (optics) and tactile (thermotics) experience in simulated realities. (B to D) Three visual scene renderings in simulated realities. (E to G) The real thermal infrared scenes corresponding to (B) to (D). (H to J) Same as (E) to (G), but with added in situ thermal rendering. Note that the cup and the hot coffee in (B) to (D) are virtual objects.



**Fig. 2.** Experimental setup and measurements. (A) Schematic experimental setup. (B to I) Measured 2D thermal infrared patterns of the characters “O,” “A,” “?”, a lock, a heart, a windmill, the division sign, and a car. (J to L) Measured 2D thermal infrared views of a cup. (M) 3D virtual rendering of a heated cup obtained combining (J) to (L).

automatically perform such a procedure. Such a technique could streamline the process and increase efficiency in rendering virtual objects.

To begin with, the generated thermal infrared signals must be transmitted to a virtual reality setup. Our metadvice is the device used to generate the real thermal infrared signals of virtual objects. The generated signals are recorded by a thermal infrared camera. The effective temperature distributions of the metadvice infrared patterns (or say, thermal images) are then transmitted to a microcomputer system via a wire or a local-area network for further processing, namely, the 3D rendering of the virtual object. It is worth noting that the transmission of thermal signals from the infrared camera to a microcomputer, like a Raspberry Pi, has been successfully tested in a recent work [61]. In Fig. 2M, the temperature of the “hot liquid” pattern happens to be close to that of the heating plate, due to the high thermal conductivity of copper ( $400 \text{ W m}^{-1} \text{ K}^{-1}$ ), used as substrate for the metadvice. Of course, the temperature of the metadvice can be varied at will.

An example of image processing algorithm is illustrated in Fig. 3. It consists of 3 main steps: image input, processing, and output. We have three 2D thermal infrared patterns and one 3D view of a cup model as input images. As shown in the upper part of Fig. 3, there are gaps between the units of the metadvice so that a thermal signal noise will be added at the unit boundaries for smoothing. Indeed, a task of image processing is to homogenize the RGB pixel along the unit boundaries by conveniently averaging the neighboring pixels and store the digital thermal views of the cup thus obtained. To any 3D model, there corresponds a 2D projection rendering taken along an arbitrary direction. We only need to cycle the direction as a variable to obtain the omnidirectional projection rendering. Here, we

restricted ourselves to the projection of a 3D cup in one particular direction (see Fig. 3). To generate the virtual output image, we performed edge detection of the 3D cup image and recorded three 2D views of the cup thermal profile. The 3D model was divided into closed areas: the upper (I), right (II), and lower (III) ones. Next, each such area was assigned the corresponding RGB pixels extracted from the thermal infrared patterns. To the area outside the cup, we assigned a set of cool-tone RGB pixels. As in general the heated 3D virtual cup is in thermal contact with its environment at the bottom, we assigned a set of warm-tone RGB pixels to the area around the cup’s bottom. The resulting image is the heated 3D virtual cup in the lower part of Fig. 3.

### Scheme to Generate a Tactile Sensing of Heating/Cooling Virtual Objects

To enable tactile thermal sensing of the generated virtual objects, one option presently under testing is to attach thermoelectric heat/cold sources [62,63] to a wearable virtual reality glove. The thermal infrared signals from the area where the wearer’s fingers touch the virtual object represent real temperatures. The virtual reality hardware can then quickly calculate the corresponding working power of the glove’s thermoelectric sources in the contact area and thus generate the corresponding temperature perception (see Fig. 3). This in situ procedure requires a minimal power consumption. To read the thermal infrared signals from the touched virtual object, we have 2 strategies. The first involves equipping the virtual reality glove with microsensors that can capture the thermal infrared signals of the contact area with the virtual object. The second strategy is to record the glove’s coordinates in the 3D coordinate system of the virtual scene generated by the glove itself. The glove only reads and elaborates the thermal infrared signals associated with the spatial coordinates of its surface.

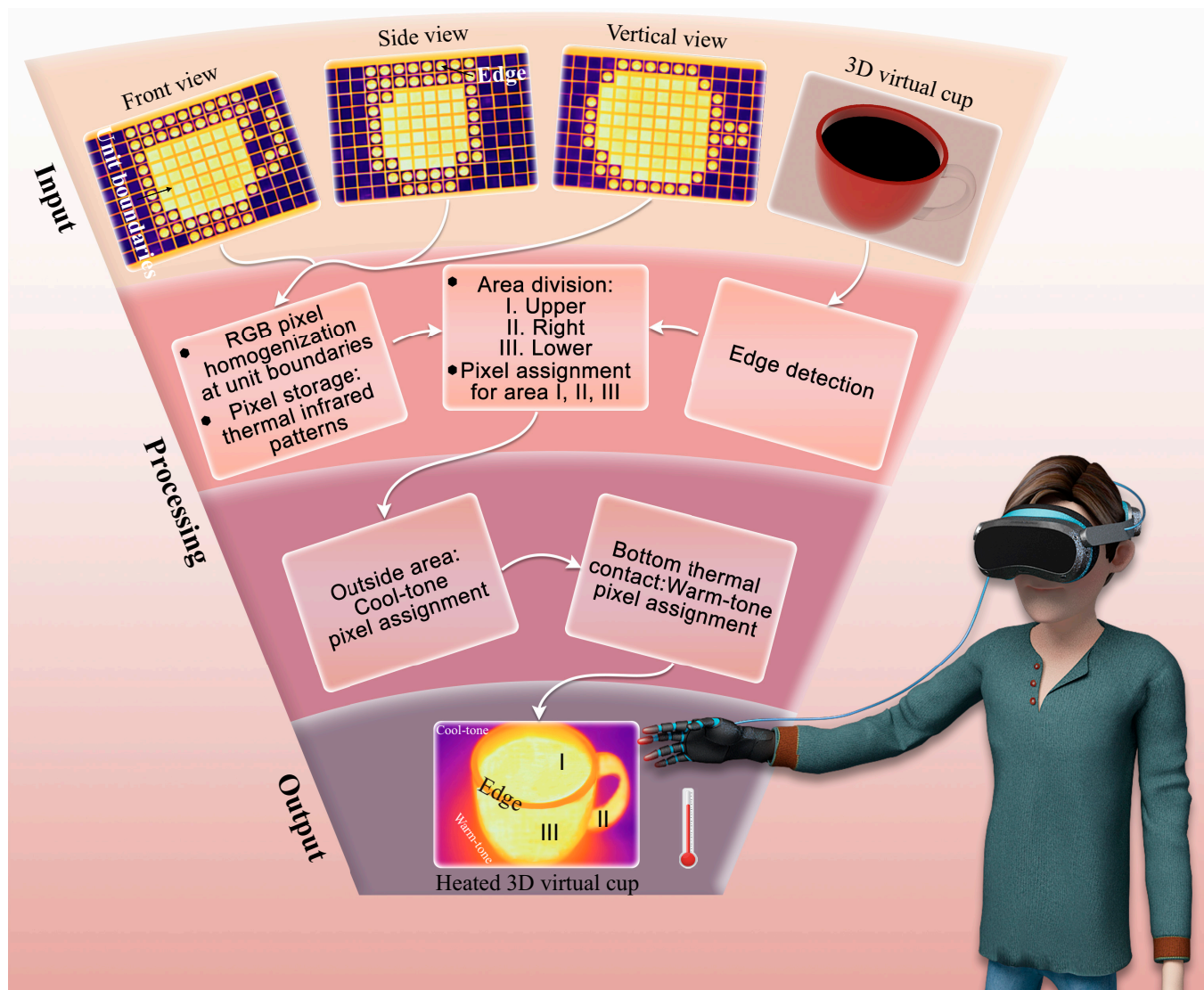
The in situ simulation of thermal reality is a noncontact human–computer interaction technology that provides a novel way of interaction by simulating real thermal perception. In our system, the user’s hand can hover over virtual objects in virtual reality, and the thermal perception of the virtual objects is realized by sensing their thermal radiation. This mode of interaction not only aligns with human lifestyle habits but also provides a more realistic perception experience in augmented reality environments, thereby greatly enhancing the user’s sense of immersion.

### Discussion

Compared with eyes and ears, skin is often overlooked as a sensory interface in the context of simulated reality. As the largest organ of the human body, the skin contains many thermal receptors responsible for our temperature sensing and thus plays a key role, when one tries to extend the simulated reality experience beyond visual, auditory, and mechanical perception. Our setup for in situ simulation of thermal realities represents a substantial step forward in this direction. This will offer users a more immersive experience and pave the way for industrial innovations in this field of technology, further expanding its applications and impact.

In Supplementary Materials S1, we derive the effective thermal emissivity of the cylindrical cavities from the basic principle of energy conservation. Such principles are not limited





**Fig. 3.** Image processing. Flowchart of an image processing algorithm for the thermal rendering of a virtual object.

to cylindrical cavities with the same material, meeting most application requirements. The metadvice we fabricated for the experiments presented here consisted of copper cubic units of the same geometry. That simple solution worked quite well with objects of uniform temperatures. However, one can think of regulating the hole depth of each unit continuously, and thus fine tuning their effective emissivity and radiation temperature independently of each other. Such a setup would be more suitable for generating the thermal image of objects with nonuniform temperature distributions (nonuniform heating/cooling). The outcome of a finite-element simulation for one such case is reported in Fig. S3. Moreover, uniform heating/cooling the bottom of the metadvice causes all its units to be heated/cooled simultaneously, which makes their temperature control quite inconvenient. In the next future, we consider achieving full temperature control of the metadvice units by resorting to voltage-driven thermoelectric heat/cold sources [62]. As a result, nonuniform thermal images of virtual objects would span over a wider, more adjustable radiation-temperature range.

## Materials and Methods

See concrete experimental details in Supplementary Materials S2.

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## Data Availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

## Supplementary Materials

Supplementary Materials S1 to S3

Figs. S1 to S3

Supplementary References

## References

- Adam JA. Virtual reality is for real. *IEEE Spectr.* 1993;30(10):22–29.
- Brooks FP. What's real about virtual reality? *IEEE Comput Graph Appl.* 1999;19(6):16–27.
- Packer R, Jordan K. *Multimedia: From wagner to virtual reality.* New York (NY): WW Norton & Company; 2002.
- Leif PB, Judy MV. Industry use of virtual reality in product design and manufacturing: A survey. *Virtual Reality.* 2017;21:1–17.
- Li Z, Lin P, Huang Y-W, Park J-S, Chen WT, Shi Z, Qiu C-W, Cheng J-X, Capasso F. Meta-optics achieves RGB-achromatic focusing for virtual reality. *Sci Adv.* 2021;7(5):eabe4458.
- Shrestha PK, Pryn MJ, Jia J, Chen J-S, Fructuoso HN, Boev A, Zhang Q, Chu D. Accommodation-free head mounted display with comfortable 3D perception and an enlarged eye-box. *Research.* 2019;2019:9273723.
- Ott R, Thalmann D, Vexo F. Haptic feedback in mixed-reality environment. *Vis Comput.* 2007;23:843–849.
- Yu X, Xie Z, Yu Y, Lee J, Vazquez-Guardado A, Luan H, Ruban J, Ning X, Akhtar A, Li D, et al. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature.* 2019;575(7783):473–479.
- He Z, Wu L, Li XR. When art meets tech: The role of augmented reality in enhancing museum experiences and purchase intentions. *Tour Manag.* 2018;68:127–139.
- Pan Z, Cheok AD, Yang H, Zhu J, Shi J. Virtual reality and mixed reality for virtual learning environments. *Comput Graph.* 2006;30(1):20–28.
- Carlos F, Sergio I-S, Carlos O. The impact of virtual, augmented and mixed reality technologies on the customer experience. *J Bus Res.* 2019;100:547–560.
- Silva JN, Southworth M, Raptis C, Silva J. Emerging applications of virtual reality in cardiovascular medicine. *J Am Coll Cardiol Basic Trans Sci.* 2018;3(3):420–430.
- Tadeja SK, Seshadri P, Kristensson PO. AeroVR: An immersive visualisation system for aerospace design and digital twinning in virtual reality. *Aeronaut J.* 2020;124(1280):1615–1635.
- Palmarini R, Erkoyuncu JA, Roy R, Fructuoso HN. A systematic review of augmented reality applications in maintenance. *Robot Comput Integr Manuf.* 2018;49:215–228.
- Liagkou V, Salmas D, Stylios C. Realizing virtual reality learning environment for industry 4.0. *Procedia Cirp.* 2019;79:712–717.
- Zhou Y, Tian L, Zhu C, Jin X, Sun Y. Video coding optimization for virtual reality 360-degree source. *IEEE J Sel Top Signal Process.* 2020;14(1):118–129.
- Colombo V, Aliverti A, Sacco M. Virtual reality for COPD rehabilitation: A technological perspective. *Pulmonology.* 2022;28(2):119–133.
- Xiong J, Hsiang E-L, He Z, Zhan T, Wu S-T. Augmented reality and virtual reality displays: Emerging technologies and future perspectives. *Light Sci Appl.* 2021;10(1):216.
- Parida K, Bark H, Lee PS. Emerging thermal technology enabled augmented reality. *Adv Funct Mater.* 2021;31(39):2007952.
- Xu H-X, Wang M, Hu G, Wang S, Wang Y, Wang C, Zeng Y, Li J, Zhang S, Huang W. Adaptable invisibility management using kirigami-inspired transformable metamaterials. *Research.* 2021;2021:9806789.
- Ren F, Gu J, Wei H, Xu G, Zhao J, Dou S, Li Y. Effect of unit cell shape on switchable infrared metamaterial VO<sub>2</sub> absorbers/emitters. *Research.* 2021;2021:9804183.
- Yang D, Hu Y, Ma D, Ge J, Huang S. Reconfigurable mechanochromic patterns into chameleon-inspired photonic papers. *Research.* 2022;2022:9838071.
- Tan X, Li Y, Wang L, Yao K, Ji Q, Wang B, Laude V, Kadic M. Bioinspired flexible and programmable negative stiffness mechanical metamaterials. *Adv Intell Syst.* 2023;5(6):2200400.
- Dudek KK, Martinez JAI, Ulliac G, Hirsinger L, Wang L, Laude V, Kadic M. Micro-scale mechanical metamaterial with a controllable transition in the poisson's ratio and band gap formation. *Adv Mater.* 2023;35(20):2210993.
- Dudek KK, Mizzi L, Martinez JAI, Spaggiari A, Ulliac G, Gatt R, Grima JN, Laude V, Kadic M. Micro-scale graded mechanical metamaterials exhibiting versatile poisson's ratio. *Compos Struct.* 2023;319(1):117151.
- Shu S, An J, Chen P, Liu D, Wang Z, Li C, Zhang S, Liu Y, Luo J, Zu L, et al. Active-sensing epidermal stretchable bioelectronic patch for noninvasive, conformal, and wireless tendon monitoring. *Research.* 2021;2021:9783432.
- Simner J. Beyond perception: Synaesthesia as a psycholinguistic phenomenon. *Trends Cognit Sci.* 2007;11(1):23–29.
- Ho HN, Van Doorn GH, Kawabe T, Watanabe J, Spence C. Colour-temperature correspondences: When reactions to thermal stimuli are influenced by colour. *PLOS ONE.* 2014;9(3):e91854.
- Erickson A, Kim K, Schubert R, Bruder G, Welch G. Is it cold in here or is it just me? Analysis of augmented reality temperature visualization for computer-mediated thermoception. Paper presented at: 2019 IEEE International Symposium on Mixed and Augmented Reality; 2019 Oct 14–18; China.
- Kurz D. Thermal touch: Thermography-enabled everywhere touch interfaces for mobile augmented reality applications. Paper presented at: 2014 IEEE International Symposium on Mixed and Augmented Reality; 2014 Sept 10–12; Germany.
- Peiris R L, Peng W, Chen Z, Chan L, Minamizawa K. ThermoVR: Exploring integrated thermal haptic feedback with head mounted displays. Paper presented at: 2017 CHI Conference on Human Factors in Computing Systems; 2017 May 6–11; USA.
- Ranasinghe N, Jain P, Karwita S, Tolley D, Do E Y-L. Ambiotherm: Enhancing sense of presence in virtual reality by simulating real-world environmental conditions. Paper presented at: Proceedings of the 2017 CHI conference on human factors in computing systems; May 6–11; USA.
- Ranasinghe N, Jain P, Thi N, Tram N, Koh K C R, Tolley D, Karwita S, Lien-Ya L, Liangkun Y, Shamaiah K, et al. Season traveller: Multisensory narration for enhancing the virtual reality experience. Paper presented at: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems; 2018 Apr 21–26; Canada.

34. Brooks J, Nagels S, Lopes P. Trigeminal-based temperature illusions. Paper presented at: 2020 CHI Conference on Human Factors in Computing Systems; 2020 Apr 25–30; USA.
35. Saito T, Zhang J, Kameoka T, Kajimoto H. Thermal sensation presentation to the forehead using electrical stimulation: Comparison with other tactile modalities. Paper presented at: 2021 IEEE World Haptics Conference; 2021 Jul 6–9; Canada.
36. Fan C, Gao Y, Huang J. Shaped graded materials with an apparent negative thermal conductivity. *Appl Phys Lett*. 2008;92(25):251907.
37. Li Y, Peng Y-G, Han L, Miri M-A, Li W, Xiao M, Zhu X-F, Zhao J, Alù A, Fan S, et al. Anti-parity-time symmetry in diffusive systems. *Science*. 2019;364(6436):170–173.
38. Wang J, Yang F, Xu L, Huang J. Omnithermal restructurable metasurfaces for both infrared-light illusion and visible-light similarity. *Phys Rev Appl*. 2020;14(1):014008.
39. Huang J. *Theoretical thermotics: Transformation thermotics and extended theories for thermal metamaterials*. Singapore: Springer; 2020.
40. Jin P, Xu L, Jiang T, Zhang L, Huang J. Making thermal sensors accurate and invisible with an anisotropic monolayer scheme. *Int J Heat Mass Transf*. 2020;163:120437.
41. Jin P, Yang S, Xu L, Dai G, Huang J, Ouyang X. Particle swarm optimization for realizing bilayer thermal sensors with bulk isotropic materials. *Int J Heat Mass Transf*. 2021;172:121177.
42. Yang S, Wang J, Dai G, Yang F, Huang J. Controlling macroscopic heat transfer with thermal metamaterials: Theory, experiment and application. *Phys Rep*. 2021;908:1–65.
43. Li Y, Li W, Han T, Zheng X, Li J, Li B, Fan S, Qiu C-W. Transforming heat transfer with thermal metamaterials and devices. *Nat Rev Mater*. 2021;6(6):488–507.
44. Jin P, Liu J, Xu L, Wang J, Ouyang X, Jiang J-H, Huang J. Tunable liquid-solid hybrid thermal metamaterials with a topology transition. *Proc Natl Acad Sci U S A*. 2023;120(3):e2217068120.
45. Zhang Z, Xu L, Qu T, Lei M, Lin Z-K, Ouyang X, Jiang J-H, Huang J. Diffusion metamaterials. *Nat Rev Phys*. 2023;5(4):218.
46. Yang F, Jin P, Lei M, Dai G, Wang J, Huang J. Space-time thermal binary coding by spatiotemporally modulated detashell. *Phys Rev Appl*. 2023;19(5):054096.
47. Zhang C, Li T, Jin P, Yuan Y, Ouyang X, Marchesoni F, Huang J. Extracting stellar emissivity via a machine learning analysis of MSX and LAMOST catalog data. *Phys Rev D*. 2022;106(12):123035.
48. Xu L, Liu J, Jin P, Xu G, Li J, Ouyang X, Li Y, Qiu C-W, Huang J. Blackhole-inspired thermal trapping with graded heat-conduction metadevices. *Natl Sci Rev*. 2023;10(2):nwac159.
49. Xu L, Huang J. Metamaterials for manipulating thermal radiation: Transparency, cloak, and expander. *Phys Rev Appl*. 2019;12(4):044048.
50. Xu L, Wang R, Huang J. Camouflage thermotics: A cavity without disturbing heat signatures outside. *J Appl Phys*. 2018;123(24):245111.
51. Zhu N, Shen X, Huang J. Converting the patterns of local heat flux via thermal illusion device. *AIP Adv*. 2015;5(5):053401.
52. Yang S, Xu L, Wang R, Huang J. Full control of heat transfer in single-particle structural materials. *Appl Phys Lett*. 2017;111(12):121908.
53. Dai G, Huang J. A transient regime for transforming thermal convection: Cloaking, concentrating and rotating creeping flow and heat flux. *J Appl Phys*. 2018;124(23):235103.
54. Xu L, Yang S, Huang J. Thermal theory for heterogeneously architected structure: Fundamentals and application. *Phys Rev E*. 2018;98(5):052128.
55. Xu L, Dai G, Huang J. Transformation multithermotics: Controlling radiation and conduction simultaneously. *Phys Rev Appl*. 2020;13(2):024063.
56. Xu L, Yang S, Dai G, Huang J. Transformation omnithermotics: Simultaneous manipulation of three basic modes of heat transfer. *ES Energy Environ*. 2020;7:65–70.
57. Shen X, Jiang C, Li Y, Huang J. Thermal metamaterial for convergent transfer of conductive heat with high efficiency. *Appl Phys Lett*. 2016;109(20):201906.
58. Yang F, Xu L, Huang J. Thermal illusion of porous media with convection-diffusion process: Transparency, concentrating, and cloaking. *ES Energy Environ*. 2019;6:45–50.
59. Xu L, Huang J. Chameleonlike metashells in microfluidics: A passive approach to adaptive responses. *Sci China Phys Mech Astron*. 2020;63(2):228711.
60. Dai G, Huang J. Nonlinear thermal conductivity of periodic composites. *Int J Heat Mass Transf*. 2020;147:118917.
61. Jin P, Xu L, Xu G, Li J, Qiu C-W, Huang J. Machine-learning-assisted environment-adaptive thermal metamaterials. ArXiv 2023. <https://arxiv.org/abs/2301.04523>
62. Guo J, Xu G, Tian D, Qu Z, Qiu C-W. A real-time self-adaptive thermal metasurface. *Adv Mater*. 2022;34(24):2201093.
63. Guo Z, Zhang Z, An K, He T, Sun Z, Pu X, Lee C. A wearable multidimensional motion sensor for AI-enhanced VR sports. *Research*. 2023;6:0154.