Ambient Material-Embodied Sensing: A Theoretical Framework for Interaction Design

Tian Min
Keio University
Yokohama, Japan
welkinmin@keio.jp

Ken-Tye Yong
The University of Sydney
Sydney, Australia
ken.yong@sydney.edu.au

Yuta Sugiura*
Keio University
Yokohama, Japan
sugiura@keio.jp

Abstract

Research and design in Human-Computer Interaction (HCI) have increasingly engaged with embodied, situated, and material-mediated forms of interaction. Across many such systems, sensing is not performed solely by embedded, off-the-shelf components, but arises through material properties and transformations. Yet HCI still lacks a coherent framework for articulating how materials themselves participate in sensing beyond serving as passive substrates. This paper introduces Ambient Material-Embodied Sensing (AMES), a generative theoretical framework that reframes sensing by foregrounding materials as the sensing medium in their own right. AMES conceptualizes it as an emergent property of material transduction, material-body coupling, and ambient computational inference. We articulate three core mechanisms and demonstrate how AMES can reinterpret existing systems while informing future design and research on material-mediated sensing in interaction design.

CCS Concepts

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

Keywords

HCI Theory, Sensing, Interface, Interaction Design Theory, Concepts and Frameworks

ACM Reference Format:

Tian Min, Ken-Tye Yong, and Yuta Sugiura. 2026. Ambient Material-Embodied Sensing: A Theoretical Framework for Interaction Design. In *Designing Interactive Systems Conference (DIS '26), June 13–17, 2026, Singapore, Singapore.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3800645.3813002

1 Introduction

HCI research has increasingly moved beyond screen-based interfaces toward embodied, situated, and material-mediated forms of interaction. Rather than being defined by discrete devices or explicit input channels, contemporary interactive systems are distributed across bodies [3, 27, 63], materials [38, 60], and environments [28, 64]. In parallel, advances in sensing and computation have enabled systems to infer interactional states from subtle physical phenomena (e.g. deformation, conductivity changes, etc.) [35, 42, 51, 52], allowing interaction to emerge from material behaviors embedded in everyday contexts.

As a result, materials now play a central role in how interactive systems sense and respond to the world. Deformable substrates, compliant structures, and composite materials are increasingly used not only to house sensors, but to shape, modulate, and sometimes generate sensing signals themselves. However, despite a rich body of work on embodied interaction [9], materiality [4, 22], HCI lacks a coherent framework and vocabulary for *articulating how materials themselves function as the sensing medium within interaction design.*

Existing perspectives offer only partial accounts of this shift. Embodied interaction foregrounds bodily action and situated practice, but does not explicitly address how sensing arises through material transformations produced by such action [14]. Similarly, research on interactive materials emphasizes expressiveness and form, yet often treats sensing as an embedded technical component rather than a material process [30, 44]. In contrast, sensing research frequently focuses on signal interpretation and computational inference, while leaving the material processes that generate those signals under-examined. Taken together, these perspectives lack a unified way of accounting for how material properties actively participate in sensing, reflecting a broader limitation in how sensing is currently conceptualized and described within HCI.

To bridge this gap, we introduce *Ambient Material-Embodied Sensing (AMES)*, a generative theoretical framework that reframes sensing in interaction design by foregrounding materials as a sensing medium. AMES conceptualizes sensing as an emergent process arising from material-body coupling and ambient computational inference, in which physical interactions and environmental conditions are transduced through material behavior into interpretable signals. This perspective shifts attention from discrete sensing components to the processes by which sensing is materially constituted in situated interaction.

By articulating a set of core mechanisms underlying how materials participate in sensing, AMES provides a conceptual structure for reasoning about these systems across diverse technologies and application domains. Abstracting over specific implementations, the framework is designed to remain stable as materials, sensing technologies, and design paradigms evolve. In doing so, it offers a generative vocabulary that supports systematic analysis of existing systems and enables new directions for interaction design grounded in material behavior.

The contributions of this paper are threefold: (1) We identify a conceptual blind spot in current HCI discourse concerning the

---

[*] Yuta Sugiura is the corresponding author.

DIS '26, Singapore, Singapore

ACM ISBN 979-8-4007-2563-0/2026/06
https://doi.org/10.1145/3800645.3813002

role of materials as active participants in sensing; (2) We introduce AMES as a generative theoretical framework that structures this phenomenon through a set of underlying mechanisms; (3) We demonstrate how AMES can be used as an analytical lens to reinterpret existing interactive systems and to generate new design and research directions in material-mediated sensing. We first motivate material-mediated sensing (Section 2), situate AMES in prior HCI theory (Section 3), articulate AMES mechanisms (Section 4), and then demonstrate how AMES reinterprets existing systems and informs design implications (Sections 5 and 6), before discussing limitations and future directions.

2 Motivation: Why Material-Mediated Sensing

Sensors in interactive systems are commonly implemented as discrete components that capture physical phenomena in the environment to support interaction and feedback. Sensing is typically realized through well-defined sensing modalities and localized points of measurement. Across a growing range of interactive systems, however, sensing is no longer realized solely through the direct measurement of human actions or environmental variables. Instead, sensing increasingly operates indirectly, by capturing changes in materials that result from interaction. In these systems, sensors are often used not to sense users or environments directly, but to observe how materials respond to contact, force, movement, or environmental conditions.

As a result, materials become central to how sensing is realized in practice. Rather than serving only as substrates that house sensing components, materials actively participate in shaping sensing outcomes. These systems extend traditional sensing approaches by distributing sensing across interactions between bodies, materials, and environments, revealing sensing as a process that cannot be fully separated from material behavior. The observations that follow highlight recurring patterns through which materials mediate sensing in contemporary HCI research.

Observation 1: Materials Reshape Sensing Modalities. In many interactive systems, materials fundamentally reshape the sensing modality through which interaction is detected. Instead of relying on predefined sensing channels, such as optical tracking, inertial measurement, or touch sensing, material behavior itself becomes the primary medium through which sensing occurs. Deformation [15, 31], compression [38, 56], stretching [51, 57], or other material responses are treated not merely as side effects of interaction, but as the signals to be sensed. As a result, sensing modalities are no longer strictly aligned with conventional sensor categories. A single material configuration may simultaneously respond to multiple physical phenomena [35, 44], blurring distinctions between force, motion, contact, and environmental change. In these systems, the sensing modality is defined less by the sensor hardware than by the material's physical properties and its interaction with the body or environment.

Observation 2: Materials Transform the Scope and Resolution of Sensing. Beyond reshaping sensing modalities, material-mediated sensing often transforms the spatial and temporal scope at which sensing operates. Rather than increasing the precision of localized measurement, these systems frequently extend sensing across larger physical regions by relying on how materials integrate interaction over space [36, 52]. In such systems, sensors are not primarily used to directly capture fine-grained human actions or environmental variables. Instead, sensing emerges from observing how material structures respond as a whole to interaction in the space. This approach enables sensing to cover areas, volumes, or dynamic fields that would be difficult to monitor using discrete sensors alone. As a consequence, materials act as intermediaries that aggregate interaction, allowing sensing to scale outward and capture macroscopic phenomena, even if local precision is reduced. Properties such as hysteresis, relaxation, accumulation, or gradual drift mean that sensing outcomes may reflect not only instantaneous interaction, but also recent histories of use or environmental conditions [35, 38, 48]. These temporal dynamics are not incidental artifacts to be corrected, but are often deliberately leveraged as part of the sensing process itself, shaping how interaction is interpreted over time rather than at isolated moments.

Observation 3: Materials Offload Sensing Complexity. A recurring pattern in material-mediated sensing systems is the use of material properties to offload complexity from sensing hardware and computational processing. Rather than relying on specialized, high-resolution, or densely deployed sensors [23, 61], designers often exploit material behavior to filter, integrate, or amplify physical signals before they reach the sensing and inference pipeline [26, 51, 53]. In such systems, relatively simple sensors are combined with carefully chosen materials to achieve sensing capabilities that would otherwise require more complex instrumentation. The material effectively performs part of the sensing work, shaping raw physical phenomena into signals that are more amenable to interpretation. This redistribution of sensing complexity—from sensors and algorithms to material behavior—appears across systems with differing goals, constraints, and technical implementations.

Observation 4: Material Behavior Becomes Implicitly Embedded in Inference. As materials increasingly mediate sensing, their behavior becomes implicitly embedded in computational inference processes. Sensing outcomes often depend on assumptions about how materials respond to interaction, even when those assumptions are usually not explicitly articulated in HCI works. Variability in material properties, environmental conditions, or patterns of use can directly affect inference results, not as noise to be eliminated, but as part of the sensing signal itself. This reliance on material behavior introduces a form of coupling between physical interaction and computational interpretation. Inference models may succeed not despite material variability, but because material responses encode structured information about interaction and context. Yet, despite this reliance, the role of materials in shaping inference is rarely described in conceptual terms within existing HCI frameworks.

Taken together, these observations point to a recurring phenomenon in contemporary HCI research: sensing increasingly emerges from the interaction between bodies, materials, and environments, rather than from discrete sensors alone. However, while these material-mediated sensing strategies are widely employed, they are often described using fragmented or system-specific vocabulary. The absence of a coherent conceptual account makes it difficult to reason systematically about such systems, compare approaches across domains, or articulate design trade-offs at a higher level.

This gap motivates the need for a framework that can capture how materials function as a sensing medium within interaction design.

These patterns suggest that sensing increasingly operates as an *ecosystemic* arrangement rather than a device capability: materials shape what becomes measurable, bodies enact sensing through use, and environments modulate both. AMES is introduced to make these relations analytically visible and designable.

3 Background

Before introducing the AMES framework, this section revisits several influential concepts in HCI that have shaped how designers think about materials, embodiment, and context in interactive systems. By outlining how these ideas frame design practice, this section establishes the conceptual landscape upon which AMES is built.

3.1 Materiality and Interactive Materials

Materiality has become a central concept in HCI research, referring not simply to the physical substance of artifacts, but to how material properties, forms, and behaviors shape interaction, experience, and practice [14, 22]. Rather than treating materials as neutral carriers of digital functionality, HCI scholars have increasingly approached materials as active constituents of interaction design, foregrounding their expressive, experiential, and performative qualities.

Building on this perspective, a growing body of work has explored interactive materials as a means of shaping interaction through physical form and material behavior. Research on computational composites and digital materials has demonstrated how properties such as softness, elasticity, texture, and continuity can be designed to afford new modes of interaction and expression, for example through bio-materials [39, 40] or deformable surfaces [44, 55]. Beyond interface behavior, research in HCI and design practice has also examined how materials participate in social and cultural practices. Studies grounded in practice theory and ethnography have shown how material properties shape ways of doing, maintenance, repair, and meaning-making in everyday life [17, 24, 47]. Frameworks such as materials experience articulate how sensorial, interpretive, affective, and performative dimensions of material engagement intertwine over time, highlighting that materials are experienced not only through immediate perception but through situated use and evolving practice [14, 43]. From this perspective, materials are understood as dynamic participants in interaction, capable of influencing how practices emerge, stabilize, and transform.

Together, these strands of research have significantly broadened our understanding of materials, positioning them as more than passive substrates or aesthetic surfaces. However, they predominantly conceptualize materials in terms of how they shape interaction output, expression, or actuation. Material behavior is typically discussed as a means of mediating how interaction is performed or experienced—for example, how deformation affords continuous control, or how texture influences perception—while sensing itself remains implicitly attributed to embedded sensors or computational components. As a result, although materiality research has richly theorized how materials affect interaction and experience, it has paid comparatively less attention to how material behavior can function as a sensing medium in its own right. The processes through which physical interactions and environmental phenomena are transformed by materials into signals for computational interpretation are often left conceptually implicit. Consequently, existing frameworks of materiality fall short of accounting for the kinds of sensing dynamics we observed in Section 2, leaving open the question of how material behavior participates not only in shaping interaction outcomes, but in constituting the sensing processes that underlie interactive systems.

3.2 Embodied Interaction and Situated Action

Embodied interaction has been a foundational perspective in HCI, shaping how interaction is understood as arising through bodily action, perception, and engagement with the physical world [9, 32]. Situated action, in turn, makes this point concrete by showing that what people actually do in interaction depends on the unfolding circumstances and contingencies of the moment, rather than on fixed plans or predefined representations [50].

These ideas have had a lasting influence on interaction design. Embodied interaction has informed a wide range of design approaches that emphasize tangible manipulation [20], physical skill [19, 21], and sensorimotor coupling [46, 54], reinforcing the view that interaction is fundamentally enacted rather than merely interpreted. In contemporary HCI, such assumptions are often taken for granted, forming a shared backdrop for how designers reason about interaction and experience. Aligned with this embodied perspective, HCI research and practice have progressively shifted sensing away from discrete input devices toward more embedded, implicit, and environmentally situated forms of sensing [49, 62, 64]. Rather than treating sensing as a foregrounded act of input, many systems rely on ambient and distributed sensing mechanisms that operate in the background, supporting embodied action without demanding explicit attention. This shift reflects a broader move toward sensing infrastructures that are tightly integrated with materials, environments, and everyday activity.

However, while the theory of embodied interaction and situated actions strongly motivates this transition in sensing practice, they leave the mechanisms of sensing conceptually implicit. Sensing is often assumed to be naturally available to the system, enabling the action—perception loop without explicit articulation of how bodily or material interaction becomes computationally perceptible. As mentioned in Section 2, sensing increasingly emerges through material-mediated phenomena—such as deformation, accumulation, or gradual environmental change—and the assumption that sensing transparently supports embodied interaction becomes insufficient. While existing frameworks provide a powerful account of how meaning arises through action in context, they offer limited conceptual resources for reasoning about how material behavior participates in constituting sensing itself. This gap motivates the need for a framework that can articulate sensing as an emergent process within interactive systems.

3.3 Ubiquitous Computing and Context-Aware Systems

Research on ubiquitous computing and context-aware systems has profoundly shaped how sensing is conceived in HCI [58]. Rather than treating sensing as an explicit act of user input or a foregrounded interaction event, these traditions position sensing as a background infrastructure that continuously supports interaction [13, 25, 27, 64]. In this view, sensing is an implicit precondition that enables systems to respond to activity, environment, and context without demanding constant attention from users, and is frequently treated as a taken-for-granted component of everyday computational environments. Within this lineage, sensing is increasingly decentered from individual devices and discrete modalities. Context-aware systems rarely rely on single sensors or direct measurements of user intent [28]. Instead, they infer interactional states and contextual conditions from heterogeneous and distributed signals, often combining multiple sensing modalities and indirect indicators. Context, in this sense, is not directly sensed but constructed through computational inference, drawing on patterns across space, time, and activity. Contemporary computational methods further enable systems to operate on noisy, partial, and indirect signals, reinforcing a shift away from explicit sensing toward inference-driven interpretation.

While ubiquitous and context-aware perspectives offer powerful accounts of system behavior, adaptation, and responsiveness, they primarily focus on how systems interpret sensed data and act upon inferred context. The processes through which sensing signals are generated—how physical phenomena are transformed into computationally meaningful representations—remain largely outside the scope of these frameworks. In particular, when sensing is mediated by materials, environments, or physical arrangements, the constitutive role of material behavior in shaping sensing outcomes is rarely articulated. As interactive systems increasingly rely on ambient and materially mediated forms of sensing, this conceptual gap becomes more pronounced. Existing frameworks provide limited resources for reasoning about sensing as a process that is materially constituted, rather than merely as an input to inference or adaptation.

4 AMES Framework

4.1 Core Insight

Ambient Material-Embodied Sensing (AMES) posits that sensing in interactive systems is not a discrete event, but an *emergent process arising from the coupling of materials, bodies, environments, and computation.* By foregrounding *materiality,* AMES situates the capacity to sense within the physical behaviors of the material itself, which transduces human action and environmental phenomena into computational signals. The *embodied* dimension highlights the mutual constitution of user and system: sensing is enacted through bodily engagement, where users modulate material states while material constraints simultaneously choreograph human practice [14]. This occurs within an *ambient* modality, where sensing is woven into the environmental fabric, pervasive yet receding into the periphery of attention [58]. Thus, AMES reframes sensing as materially grounded, performative, and inextricably linked to the background of everyday life.

Building on this foundation, AMES serves as a conceptual lens for interrogating how sensing is constituted within interactive systems. The framework explicates how *material behavior*, *embodied engagement*, and *ambient computation* jointly shape the sensing process. In the following sections, we first delineate the analytical scope and design orientation of AMES. We then detail the framework's three principal mechanisms—*material transduction*, *Embodied Coupling*, and *ambient inference*—which structure how sensing takes form across diverse interactive contexts.

4.2 Analytical Scope and Design Orientation

The analytical scope of AMES is defined by a shift in the locus of sensing: from *discrete components* attached to objects, to the *material medium* of the object itself. We distinguish AMES from interactive systems that rely on extrinsic instrumentation—where sensors remain distinct, "black-boxed" hardware separate from the form they augment. Instead, AMES encompasses systems where sensing is intrinsic to the material substrate, relying on the continuous, often non-discrete properties of matter (e.g., conductivity, compliance, optical transmittance) to register interaction. By framing the material as a sensing medium, the framework directs analytical attention to how physical substances transduce energy and information through their inherent behaviors.

As a result, the design orientation of AMES moves beyond the selection and assembly of discrete sensing hardware. It instead frames interaction design as the *orchestration of material behaviors.* In this view, the designer's role transforms from integrating components to identifying, amplifying, and mapping inherent material properties—such as viscoelasticity in textiles or conductivity in fluids—to meaningful computational states [37, 51]. AMES thus operates as a generative guide: it prompts designers to ask how the physical constitution of an object might itself become the site of sensing, rather than merely a container for it. This orientation privileges a "material-first" approach, where the capabilities of the system emerge from the specific physical affordances of the substrate.

4.3 Principal Mechanisms

To operationalize AMES, we delineate three principal mechanisms that structure the sensing process: **Material Transduction**, **Embodied Coupling**, and **Ambient Inference**. These mechanisms are not sequential steps in a pipeline, but rather distinct logical layers that bridge the physical and the computational. At the foundational layer, *Material Transduction* concerns the physical capacity of the substrate to register energy and environmental change. This physical layer is animated through *Embodied Coupling*, which describes the bidirectional interplay where user actions modulate material states, while material affordances simultaneously constrain and choreograph human practice [8, 11]. Finally, *Ambient Inference* operates at the interpretative layer, where the system resolves the inherent ambiguity of material signals by leveraging contextual priors, translating tangible material changes into meaningful interaction intentions. Together, these mechanisms articulate *a trajectory from the physics of matter, through the performance of the body, to the intelligence of the system.*

4.3.1 *Material Transduction.*

Material transduction constitutes the foundational layer of AMES, referring to the process by which a material substrate directly converts physical energy—mechanical, thermal, or chemical—into detectable state changes. In conventional engineering, transduction is typically confined to the microscopic

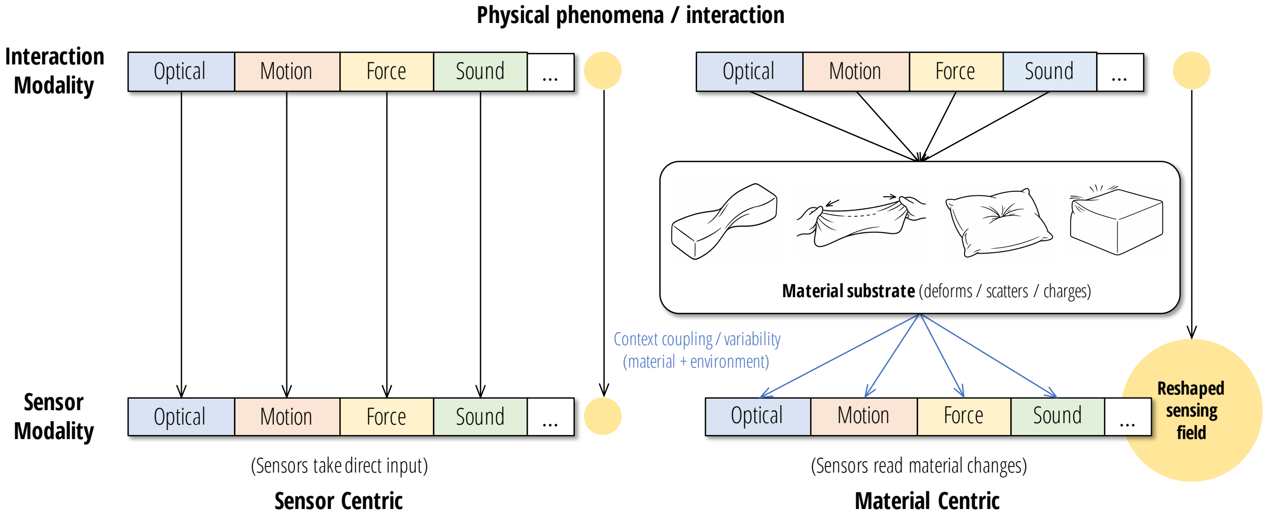

Figure 1: Sensor-centric and material-centric transduction. Left: conventional sensing maps interaction phenomena directly into sensor modalities. Right: in material-mediated sensing, interaction and environmental phenomena first produce macroscopic changes in a material substrate, which are then read out by sensors, introducing context-dependent variability, and reshape the sensing field (yellow shadow of circle).

structures of discrete sensors (e.g., the capacitive plates within an accelerometer), remaining opaque to the user. In contrast, AMES situates transduction at a macroscopic scale, where the material itself acts as the primary medium for modality conversion. This shift introduces a level of **phenomenological visibility**: users can perceive the sensing mechanism through the observable behaviors of the material, such as the stretching of a conductive textile [57], the color shift of the Flavobacteria [16], or the compression of a hygroscopic structure [38]. Here, the "sensor" is no longer a component added to an object, but is the object's materiality in action.

This perspective necessitates a re-evaluation of the role of traditional electronic instrumentation. Within AMES, standard sensing components (e.g., electrodes, accelerometers, piezoelectric films, or optical receivers) are not discarded but are reframed as **signal pickup mechanisms** rather than the locus of sensing. The primary "sensing" event occurs when the material properties are modulated by the environment or human action; the electronics merely serve to harvest and digitize these material shifts. This distinction is particularly evident in self-powered, energy-harvesting materials [30, 35, 48, 62], where the material transduction is so robust that it generates its own power source, further blurring the boundary between the physical substrate and the sensing instrumentation.

Crucially, AMES embraces the inherent complexities of material behaviors that are often treated as "noise" in precision engineering. Materials exhibit **non-linear dynamics**, such as hysteresis, viscoelasticity, and environmental sensitivity. For instance, a biological material may change its conductivity not just based on immediate interaction, but based on changing moisture over time [35]; a textile may show resistance drift due to its mechanical history [51]. Rather than suppressing these properties, AMES views them as rich informational resources. These temporal and environmental dependencies—accumulation, decay, and fatigue—embed the sensing process within the broader context of the physical world, allowing the system to capture not just a discrete input event, but the ongoing history of the material's engagement with its environment.

Material transduction does more than convert physical phenomena into a measurable signal; it can also *externalize* sensing by relocating part of the sensing function from the sensor package into the material substrate and its boundary conditions. In this view, the sensor becomes a readout of material state, while the material performs physical work that is otherwise “inside” sensors: coupling to the phenomenon, shaping selectivity, and structuring what becomes observable. The result is a *sensing field*—a spatially and temporally distributed material response, that encodes interaction and environmental forces as patterns rather than isolated measurements. This field may expand the effective spatial extent of sensing (from point to surface or volume), introduce temporal structure through accumulation or hysteresis, and increase discriminability by transforming hard-to-measure phenomena into legible material configurations. Crucially, because the sensing field is enacted through manipulation, its structure is also shaped by Embodied Coupling: users do not merely trigger sensing, but actively configure the material conditions under which sensing becomes interpretable.

4.3.2 *Embodied Coupling.*

While material transduction provides the physical capacity for sensing, **Embodied Coupling** activates this capacity through human engagement. In AMES, interaction is not modeled as a discrete transmission of commands (user input → system output), but as a continuous, bidirectional negotiation between the human body and the material substrate. This mechanism posits that sensing emerges from the physical loop where the body modulates the material, and the material, in turn, shapes the body's action. A useful implication of this coupling is that, once sensing is externalized into a material substrate, users are no longer acting on a sensing device but on a *sensing field* constituted by the material's state. Through pressing, shearing, stretching, or repositioning, users effectively configure the spatial and temporal patterns that the system will later interpret. In this sense, Embodied Coupling is not only about experience; it is a mechanism through which the sensing field is *produced, shaped, and stabilized* in practice—often via material forms that guide people toward interaction patterns.

At the center of this mechanism is its connection to the concept of **material agency** [14]. Materials are not passive recipients of force; they actively constrain and choreograph human gestures through their mechanical and tactile properties. A stiff, elastic fabric "asks" to be stretched with specific force; a textured surface "invites" a particular speed of stroking. This phenomenon—where the material solicits specific somatic responses—is critical for sensing. It ensures that the generated signals are not random noise, but structured patterns derived from the material's physical script. For instance, the resistance of a smart foam doesn't just measure pressure; it physically shapes the user's posture, ensuring the sensing event occurs within a predictable, material-defined envelope [38].

Consequently, Embodied Coupling reframes sensing as a **performative act**. The user does not merely *trigger* a sensor but *performs* the interaction in dialogue with the material. This coupling is deeply situated in everyday practice: the way a user grips a steering wheel, sits on a cushion, or wears a garment is continuously adjusted in response to the material's feedback. AMES leverages this reciprocal loop, treating the physical constraints of the material not as limitations, but as essential scaffolding that structures user behavior into recognizable, sensible data streams.

4.3.3 Ambient Inference. Ambient Inference constitutes the computational layer that translates physical material changes into digital meaning. Unlike precision-engineered sensors that output deterministic values (e.g., a specific signal pattern responding to a specific interaction), material-embodied sensing often generates signals that are noisy, non-linear, and entangled with environmental variances. To overcome this inherent **ambiguity**, AMES relies on an inference logic that is **probabilistic** and **context-aware** rather than purely deterministic.

This mechanism functions by situating the raw material signal within a broader **contextual model**. Because the material is physically embedded in an object (e.g., a piece of furniture or a surface), the computing system of AMES can leverage strong **semantic priors** about the object's affordances to disambiguate the signal. For example, a noisy signal change in a smart cushion needs not be deciphered in isolation [52]; knowing that the object is placed on a door allows the system to probabilistically infer "opening" or "closing" instead of attributing the signal to random deformation [13]. Here, the burden of precision is shifted from the hardware (the material consistency) to the software (the inferential logic), which synthesizes material data with environmental context—time of day, location, or user routine—to construct a coherent interpretation of user intent.

Furthermore, Ambient Inference addresses the challenge of variability inherent in material fabrication and deployment. Since no two material patches may behave identically, the inference layer must move beyond rigid, one-time calibration toward **adaptive learning**. This implies a computational architecture capable of evolving: recognizing patterns of use that emerge over time and adapting to the gradual drift or settling of material properties [53]. By treating ambiguity as a feature of the analog world rather than a defect, Ambient Inference bridges the gap between the messy, continuous reality of material behaviors and the discrete logic of interactive systems.

5 Deconstructing Material-Embodied Sensing in Prior Works

To illustrate how AMES can be applied, this section analyzes 12 analytical exemplars on material-mediated sensing (Table 1). These cases are not intended as a comprehensive or statistically representative sample of the literature. Rather, because the goal of this paper is to articulate AMES as a design-theoretical lens, the examples were chosen as analytical exemplars that make the framework especially legible across a heterogeneous set of sensing arrangements. In particular, the set was assembled to span different material substrates, interaction forms, and sensing configurations, while covering the three primary transduction families through which material behavior becomes computationally actionable.

Rather than organizing these systems by application domain, we group them by their primary **Material Transduction** modality. This transduction-oriented taxonomy foregrounds how different material forms—solids, fibers, fluids, and living materials—turn human action and environmental change into signals that become legible to computation. We structure the analysis into three transduction families: (1) *Mechanical & Kinetic* (2) *Optical & Light-Mediated* and (3) *Electrical & Electromagnetic.* Within each family, we briefly highlight how Embodied Coupling and ambient inference shape the sensing arrangement. For each case, we first identify its primary mode of material transduction, and then examine how Embodied Coupling and ambient inference contribute to making the resulting signals meaningful in practice.

5.1 Mechanical & Kinetic

Mechanical and kinetic transduction is a prevalent family of material-mediated sensing, in which material form and structure shape how mechanical energy is routed, filtered, and expressed as measurable change. In AMES terms, these systems show how macro-geometry and structural waveguiding do more than hold sensing components: they act as forms of physical pre-processing that condition what interactions become legible to subsequent sensing and interpretation, often in ways that invite specific embodied engagements and support background inference.

Structural Logic as Physical Pre-computation. One fundamental approach leverages a material's macro-geometry to constrain how deformation propagates and, in doing so, shape what becomes legible to sensing. In Slyper et al. [49], the V-groove geometry of a silicone substrate can be understood as a physical logic gate: interaction-driven deformation produces a discrete mechanical

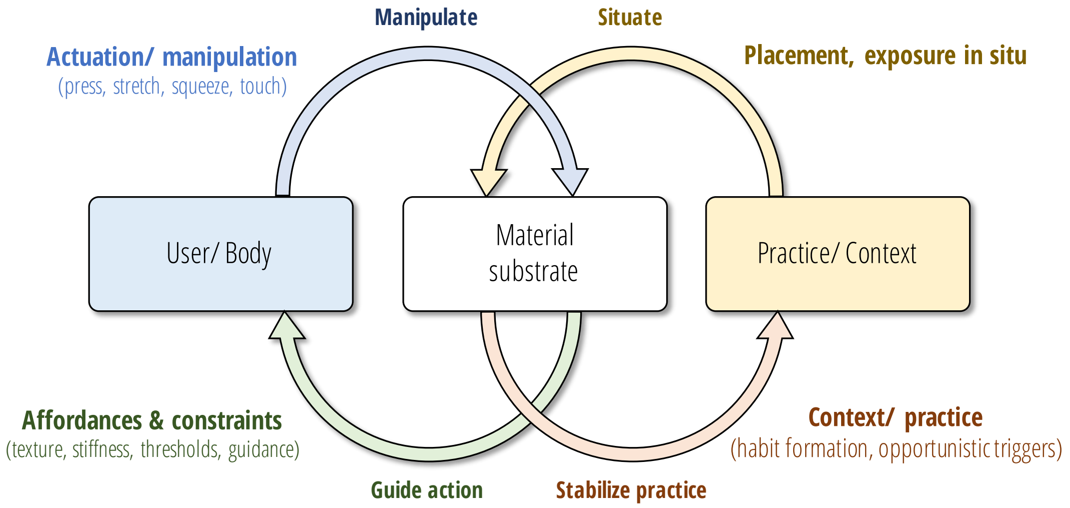

Figure 2: Embodied coupling in AMES. Materials mediate a bidirectional loop: users manipulate materials, while material affordances and constraints guide action. In parallel, placement and exposure embed materials in situated contexts, shaping practice through habits and opportunistic triggers.

Table 1: Technical mapping of material-mediated sensing systems via the AMES framework, Categorized by three transduction families of *Mechanical & Kinetic*, *Optical & Light-Mediated* and *Electrical & Electromagnetic*.

Family	System	Input → Sensing Modality	Material	Mechanism
Mech.	Slyper et al. [49]	Bend → Contact	Silicone	**Structural Occlusion**: V-grooves modulate circuit connectivity.
	Acoustruments [26]	Slide → Frequency	3D Plastic	**Acoustic Waveguide**: Cavity geometry modulates resonant frequencies.
	SoundOff [13]	Movement → Resonance	Metal Reeds	**Vibro-acoustic ID**: Mechanical agitation triggers ultrasonic resonance.
Opt.	FuwaFuwa [52]	Squeeze → Reflectivity	Fiberfill (Cotton)	**Internal Scattering**: Fiber density shift modulates light path.
	Sugiura et al. [51]	Stretch → Transmittance	Elastic Fabric	**Porosity Shift**: Fabric gaps modulate light transmission levels.
	Seeing the Wind [36]	Airflow → Transmittance	Aqueous Mist	**Mie Scattering**: Fluid density changes modulate laser reflection.
	OptoSense [62]	Hover → Photovoltaic	OPV Thin-film	**Photoelectric Effect**: Ambient light harvesting as signal source.
Elec.	iSkin [57]	Touch → Capacitance	Carbon-PDMS	**Layered Capacitance**: Distance/area shift in multilayer electrodes.
	foamin [56]	Press → Resistance	Conductive Foam	**Piezoresistivity**: Porous structure modulates conductive paths.
	MetaSense [15]	Shear → Capacitance	Conductive TPU	**Geometric Capacitance**: Grid deformation modulates capacitance.
	Liu et al. [30]	Various → Pulse	PTFE/Cu Foil	**Triboelectrification**: Contact-separation generates transient pulses.
	SoilSense [35]	Press → Voltage	Soil	**Bioelectrochemical Modulation**: Pressure shifts ion transport in SMFCs.

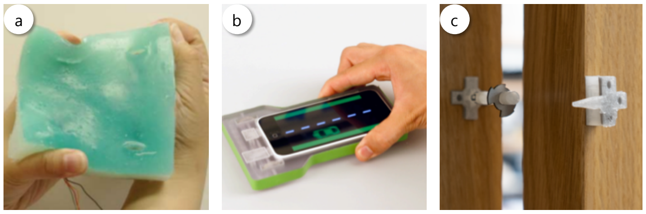

Figure 3: Examples of mechanical and kinetic transduction: a. Slyper et al. [49]; b. *Acoustruments* [26]; c. *SoundOff* [13]

state that is established in the structure before any electronic sensing or computation (Figure 3 a). When users press and release the surface, the material's stiffness introduces a tactile threshold—a haptic “snap”—that aligns embodied perception with the system's binary transition. From an AMES perspective, this represents a form of computational offloading in which structural form stabilizes state changes and reduces ambiguity in the resulting signal, anchoring interpretation in consistent mechanical constraints rather than relying solely on statistical inference downstream.

Acoustic Cavities as Reconfigurable Waveguides. A related approach shifts material transduction from bulk deformation to the modulation of waves traveling through internal cavities. *Acoustruments* [26] exemplifies this strategy by treating the air inside 3D-printed voids as a *reprogrammable signal carrier* (Figure 3 b). Rather than instrumenting each point of contact, interaction is mediated by users' fingers reshaping the acoustic boundary conditions of the cavity, altering impedance and resonance in ways that become legible to sensing. The layout of apertures invites a particular dexterity, turning input into a form of embodied manipulation grounded in fluid-structure resonance. From an AMES perspective, the system distinguishes gestures by leveraging how moment-to-moment changes in cavity geometry produce characteristic acoustic signatures, reducing the burden on downstream inference by embedding discriminability into the material configuration itself.

Passive Resonance as Embedded Identity. A more autonomous configuration emerges when a material's morphology serves as a stable identifier that can be sensed through passive resonance. *SoundOff* [13] illustrates this idea through what is described as "geometric determinism," where the length of a metal reed yields a characteristic resonant signature that can function as a physical fingerprint (Figure 3 c). Rather than assigning identity through editable digital markers, the system leverages resonance properties that are tied to the artifact's form and remain discriminable despite typical variability in mounting and everyday conditions. Interaction in this setting is opportunistic: everyday motion—such as a door swing or a drawer slide—provides the kinetic excitation needed to elicit the reed's vibration, which can then be sensed and interpreted. This anchors digital semantics to the physical artifact by making identification arise from the object's own vibrational response, enabling environments to be recognized through their material signatures. From an AMES perspective, *SoundOff* exemplifies how material transduction (passive resonance) and ambient operation (use-driven excitation) can jointly support sensing without requiring continuous power delivery beyond the interaction itself.

Taken together, the mechanical and kinetic cases above highlight a recurring configuration within AMES: sensing is shaped not only by instrumentation, but by how material form and structural constraints condition mechanical energy before it is sensed and interpreted. Sensing logic is often embedded in the material arrangement itself—through geometry, stiffness, and waveguiding—so that parts of the discretization and ambiguity reduction occur physically rather than being deferred entirely to software.

Across these examples, material behavior constrains and transforms continuous bodily action into more interpretable state changes, effectively shifting some of the burden of disambiguation from downstream computation to the physics of the interface. This also strengthens Embodied Coupling: the user's felt thresholds and resistances can align with the system's state transitions, making interaction legible through touch and movement as well as through data. More broadly, these cases suggest that when morphology is designed with transduction in mind, sensing can become tightly integrated with the artifact itself, blurring the boundary between physical form and interactive function.

5.2 Optical & Light-Mediated

Optical transduction in AMES shifts attention from camera-centric vision toward material-mediated optics, where interaction is encoded through how materials modulate, scatter, transmit, or convert light. In these systems, light functions as a sensing carrier whose observable patterns are shaped by a material's morphology (e.g., thickness, microstructure, and surface finish) and by ambient conditions such as illumination and occlusion. Rather than treating optics as a separate sensing channel layered onto an object, these works embed sensing into the optical behavior of the material itself, making interaction legible through changes in light propagation and appearance.

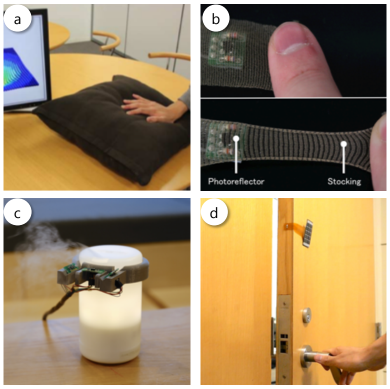

Figure 4: Examples of optical and light-mediated transduction: a. *FuwaFuwa* [52]; b. *Sugiura et al.* [51]; c. *Seeing the Wind* [36]; d. *OptoSense* [62]

Volumetric Scattering and Porosity Modulation. A common optical strategy leverages a material's internal structure to shape light propagation in ways that become sensitive to deformation. *FuwaFuwa* [52] relies on scattering within a soft, fibrous volume, where the cotton-like material functions as an optically diffusive medium. When users squeeze the material, they reconfigure fiber density and contact, altering scattering and reflection paths; this volumetric change is transduced into measurable intensity patterns (Figure 4 a). Similarly, *Sugiura et al.* [51] exploits porosity modulation in elastic fabrics, where stretching or shearing changes pore geometry and, in turn, modulates light transmittance (Figure 4 b). Across both examples, Embodied Coupling is integral to how sensing is enacted and understood. Material qualities such as stretchiness and fluffiness guide how users apply force and deformation, while optical flux provides a low-ambiguity signal of the resulting material state. From an AMES perspective, these systems embed sensing in the coupling between soft manipulation and light transport, making interaction legible through material-mediated optics rather than through explicit input devices.

Aerosol Scattering as an Interactive Medium. Optical transduction can also be realized through fluids, where light is structured by the motion of suspended particles rather than by a fixed solid form. *Seeing the Wind* [36] exemplifies this approach by using transient mist as a volumetric optical substrate: aerosol particles scatter laser light from time-of-flight (ToF) sensors, making otherwise invisible airflow patterns observable (Figure 4 c). When users blow air or wave a hand nearby, they reshape the flow field that carries and redistributes the mist, producing characteristic changes in the particle cloud. Crucially, the mist forms an *externalized sensing field*: rather than measuring airflow at a single point, the system leverages a distributed material response in space. The aerosol does not merely "visualize" air; it carries and integrates airflow disturbances over a volume, translating transient forces into spatiotemporal patterns of scattering that can be sampled by sparse sensors. In this sense, the field of sensing is relocated from the sensor package to the ambient medium itself. From an AMES perspective, the material transduction here lies in aerosol scattering, while sensing is enacted through embodied interaction with an ambient medium rather than direct contact. Because the resulting signals are inherently dynamic and context-dependent, interpretation relies on ambient inference over spatial and temporal patterns in the mist, allowing the system to estimate airflow direction and strength. This case illustrates how material-mediated sensing can render environmental forces legible by coupling fluid dynamics with optical observation.

Photovoltaic Conversion. Optical transduction can extend beyond modulating external light to converting it into electrical energy that is directly usable for sensing. *OptoSense* [62] illustrates this approach through photovoltaic transduction, using organic thin films that function both as power-generating layers and as spatially distributed sensing elements (Figure 4 d). From an AMES perspective, this configuration tightly couples energy and signal: changes in illumination simultaneously alter the available power and produce measurable voltage patterns. Interaction is enacted through shadow casting. As a user's hand occludes ambient light, it produces localized and time-varying drops in photocurrent and voltage that the system can sense and interpret. In this framing, ambient light serves as an ever-present carrier for interaction, while gesture is expressed through its modulation via occlusion. This enables opportunistic sensing that can operate with reduced dependence on dedicated power delivery at the sensing surface, and it expands the sensing locus from a discrete input point to an illuminated area where material coverage and environmental light jointly shape what can be sensed.

The optical cases above show how light-based sensing in AMES is constituted through materials that modulate, redistribute, or convert optical flux. These systems do not simply measure incident light; they embed sensing in the material mechanisms that shape light transport and availability. Across these configurations, the material functions as a form of optical pre-processing that conditions what can be sensed before downstream computation. This shifts emphasis away from camera-centric imaging toward material-mediated optics, where sensing depends on how morphology, state of matter, and ambient illumination jointly structure the signal. More broadly, these cases suggest design opportunities in treating light as a pervasive carrier and material optics as a programmable resource—while also foregrounding the role of ambient inference in handling variability introduced by changing environmental conditions.

5.3 Electromagnetic & Capacitive

Electrical and electromagnetic transduction is a dominant family in interactive sensing, in part because it couples directly to how computing systems measure and interpret signals. Within AMES, this family foregrounds how material electrical behavior—such as impedance, capacitance, charge generation, or electrochemical potential—serves as the sensing medium through which touch, deformation, proximity, and environmental change become computationally legible. These systems often distribute sensing across material composition, geometry, and electrode arrangement, making interaction detectable through changes in electrical state that are shaped by both use and context.

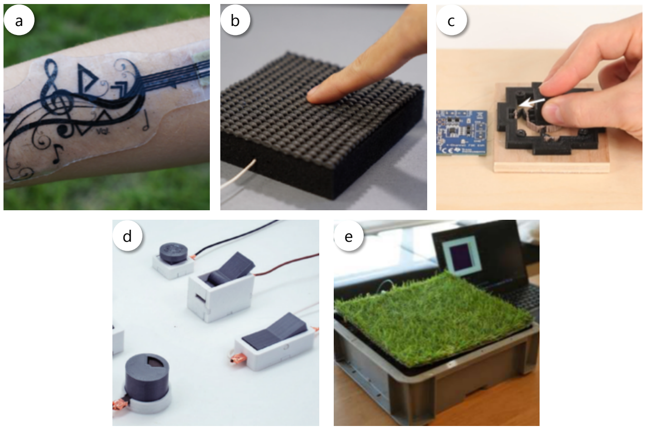

Figure 5: Examples of electromagnetic and capacitive transduction: a. *iSkin* [57]; b. *foamin* [56]; c. *MetaSense* [15]; d. Liu et al. [30]; e. *SoilSense* [35]

Impedance Modulation. A widely used electrical strategy relies on modulating a material's impedance—typically through changes in resistance or capacitance—under touch, deformation, or proximity. *iSkin* [57] and *foamin* [56] exemplify this approach through compliant, body- and object-conforming structures that turn contact and pressure into measurable electrical change (Figure 5 a and b). From an AMES perspective, the material functions as a flexible transduction layer: it conforms to complex surface topology while distributing interaction across its geometry. When users touch or deform these substrates, they change conductive pathways or electrode separation (e.g., particle spacing in composites, or distances between layered electrodes), producing impedance variations that can be sensed and interpreted. In practice, such signals are often shaped by fit, motion, and environmental factors, motivating inference that is robust to variability in everyday use.

Architected Capacitance in Cellular Materials. A complementary strategy embeds sensing not primarily in material composition, but in how engineered geometry couples mechanical deformation to electrical state. *MetaSense* [15] illustrates this approach using architected cellular structures whose collapse under shear or compression produces characteristic changes in capacitance between internal walls (Figure 5 c). In this sense, the material performs a form of geometric pre-processing: the deformation pathway imposed by the unit-cell design shapes how multi-axis forces are expressed as an electrical signature. From an AMES perspective, this configuration makes interaction legible by encoding directional sensitivity into structure. Users do not merely apply force to an instrumented surface; they engage a designed mechanical response that constrains how forces propagate and how capacitance changes are produced. As a result, downstream interpretation can rely on signal structures that are already shaped by structural priors, improving discriminability between different modes of interaction and reducing ambiguity introduced by unconstrained motion. The unit-cell response also invites particular forms of manipulation (e.g., shear vs compression), aligning bodily action with the material's directional sensitivity.

Energy-Coupled Transduction and Self-Powered Signals. A further extension of electrical transduction couples sensing with energy generation, where interaction supplies excitation and the resulting electrical response is both a signal and a source of usable power. In triboelectric nanogenerator (TENG)-based interfaces [30], contact electrification during tapping or sliding produces transient voltage pulses that can be used for event detection and, in some configurations, to support low-power transmission (Figure 5 d). Here, sensing is enacted through the same physical exchange that generates charge, tightly linking the material interaction to the electrical signature. *SoilSense* [35] extends this idea into bioelectrochemical transduction by leveraging soil-based microbial fuel cells as a sensing substrate (Figure 5 e). Pressing the soil or changing its moisture content alters ionic transport and microbial metabolic activity, which in turn changes the cell's electrical output. Compared to TENG interfaces, these signals evolve over longer time scales and are strongly shaped by environmental conditions, making interpretation inherently contextual. From an AMES perspective, such systems foreground how ambient coupling and inference become central when the sensing medium is living or ecological: interaction is mediated through material-environment dynamics rather than through isolated device components. These examples suggest sensing interfaces that are not only fabricated, but also maintained and tuned through ongoing material-environment relations.

Viewed through the AMES lens, this family also clarifies a central tradeoff of material-mediated electrical sensing. On one hand, electrical state changes can be tightly aligned with computation, enabling scalable sensing surfaces, conformal form factors, and in some cases self-powered operation. On the other hand, electrical signals are often inseparable from ambient conditions and material history, making inference and calibration part of the sensing constitution rather than a downstream add-on. Additionally, these cases suggest design opportunities in treating impedance, capacitance, and electrogenic potential as "designable" material resources—while foregrounding how embodied engagement and ambient context jointly shape what becomes interpretable as interaction.

6 Discussion

With these re-interpretations in place (Section 5), we turn to the broader implications of AMES for interaction design and HCI research.

6.1 What AMES Adds

AMES contributes a vocabulary and analytical lens for reasoning about sensing as a constitutive part of interaction. Across HCI, many systems already rely on materials to shape what can be sensed—through geometry that discretizes motion, substrates that redistribute optical flux, or electrogenic media that couple interaction with energy and ecology. Yet these arrangements are often described in device-specific terms (e.g., as a particular sensor, fabrication, or instrumentation choice), *leaving the material mechanisms that make sensing possible under-articulated.* AMES makes these mechanisms explicit by framing sensing as a relational process grounded in material transduction, enacted through Embodied Coupling, and interpreted through ambient inference. This framing allows designers and researchers to compare heterogeneous systems through a shared conceptual structure, to diagnose why certain material interfaces are robust or fragile in practice, and to generate new design directions by treating material behavior itself as a designable sensing resource.

6.2 Design Opportunities

AMES surfaces design opportunities that shift attention from sensing components and inference pipelines toward the material conditions under which sensing becomes possible. Rather than treating sensing as a problem to be solved primarily through computation, these opportunities invite designers to treat material behavior as a first-class design resource—one that can structure signals, guide action, and shape interpretation. Across these opportunities, designers can consider how material change is produced (*transduction*), how it is enacted in practice (*coupling*), and how it is made understandable to both systems and users (*inference*).

Design interaction through transduction. Material-mediated sensing highlights that interaction can be designed by first *asking how a material system converts physical phenomena into computationally legible change.* In this framing, transduction is not merely an engineering step but a generative design space: designers can start from naturally occurring material behaviors and deliberately shape how those behaviors yield stable, discriminable signals. Importantly, this space is rarely one-to-one mappings. Materials are inherently composite in the sense that a single substrate often participates in multiple physical regimes at once—mechanical motion can co-occur with acoustic resonance, surface deformation can co-vary with optical reflectance, and moisture or temperature can modulate electrical impedance. A transduction-oriented approach therefore invites designers to reason about relationships *across modalities*: one phenomenon producing multiple observable traces (one-to-many), multiple phenomena collapsing into a shared material response (many-to-one), or coupled transformations in which changes in one modality carry information about another (many-to-many). Thinking in these terms encourages designs that treat materials as cross-modal translators and physical priors, enabling richer sensing strategies through redundancy, complementarity, or deliberate ambiguity—so that computation reads signals that have already been meaningfully structured by matter, rather than attempting to recover intent from raw measurements alone.

Design for enactment and ambient coupling. Beyond transduction, AMES highlights *enactment and ambient coupling* as a second generative design space: material sensing is enacted, and signals emerge through how people manipulate, inhabit, and move around materials in place. This suggests that designers may attend both to the *enactment space* a material affords and to the *situated coupling* through which it becomes part of everyday life. At the material scale, tactile qualities, thresholds, geometry, and zones of compliance can be used to deliberately narrow a broad space of possible movements into a smaller set of interaction patterns, turning affordances into a physical "grammar" that choreographs action into interpretable change [14]. At the same time, because material interfaces are encountered in context, their placement—its availability, exposure, and relationship to routines—not only shapes which actions become natural opportunistic triggers (e.g., reaching, walking, opening, resting) and how often they recur, but also conditions how sensing can be negotiated, attenuated, or avoided in practice [7]. In this sense, deployment conditions partly determine the *sensing field* a material establishes (its spatial extent, accessibility, and the region of space/time it can register), while habitual embodied action stabilizes which parts of that field are repeatedly "written" through use. At the same time, the very embodied and ambient arrangements that enable such coupling also define how sensing boundaries are encountered and regulated in situ: whether sensing can be covered, interrupted, approached, or distanced through ordinary bodily conduct [1]. Designing for the ambient, therefore, means not only aligning sensing with recurrence, but also shaping how it remains legible, negotiable, and situated within in-situ practice rather than interrupting it with explicit commands.

Design for interpretability and legibility. As sensing becomes increasingly inference-driven and distributed, users may have limited access to how systems "*know*," which can increase uncertainty and make errors harder to diagnose. A key opportunity in AMES is that material change is often inherently perceptible: deformation, optical variation, resistance, sound, or other expressions can provide cues that help users form a relatively intuitive model of what is being sensed. Designing for legibility does not require exposing technical details; rather, it involves aligning what the system interprets with what users can feel or observe in the material itself, so that action, material response, and system interpretation remain mutually accountable. Importantly, interpretability in AMES also concerns what happens *when* inference is uncertain. Designers can make ambiguity tolerable by shaping how evidence accumulates and how states are communicated—e.g., using gradual material transitions, hysteresis, or thresholds to avoid jitter; providing lightweight confirmation that indicates what the system currently believes; and offering recourse such as reset, recalibration, or corrective gestures when interpretation drifts. These moves turn interpretability into a property of the interaction loop rather than a post-hoc explanation of an algorithm. In practice, legible material behavior can reduce the perceived black-box nature of sensing, support faster learning, and enable users to comprehend and appropriate systems in everyday settings [33].

6.3 Design Challenges and Trade-offs

Material-mediated sensing does not simply extend the designer's toolbox; it also reconfigures where sensing "lives" in an interactive system. A recurring trade-off concerns *who—or what—does the sensing work.* When sensing is delegated to integrated, purpose-built sensors, designers often gain precision, repeatability, and portability across contexts, at the cost of introducing discrete components and explicit instrumentation. In contrast, when sensing is constituted through external materials and their coupling to everyday environments, designers gain access to rich, expressive, and often highly sensitive signals that can be embedded into form and practice. However, this shift also redistributes uncertainty: variability that is typically abstracted away by standardized sensors becomes part of the sensing constitution itself. AMES is therefore not a call to replace sensors with materials, but a lens for making visible the conditions, costs, and responsibilities that arise when sensing is grounded in material behavior.

Context drift and environmental dependence. Because material signals are shaped by ambient conditions, material-mediated sensing is often inseparable from factors such as illumination, humidity, temperature, wear, mounting, and gradual settling. Prior work has repeatedly acknowledged these dependencies—alongside fabrication variability—as practical limitations for deploying material-mediated sensing systems outside controlled settings [35, 36, 38, 52]. Such influences can be productive, enabling opportunistic and in-situ sensing, yet they also introduce drift and cross-context fragility that complicate interpretation. Importantly, these variations are often not well-modeled as stationary "noise": they can be structured, state-dependent, and entangled with the interaction itself, making them difficult to handle with standard supervised learning assumptions that rely on stable training distributions. Designing with AMES therefore requires treating context as a constitutive variable to be managed rather than an external disturbance to be eliminated. At the interaction level, designers can reduce ambiguity by shaping transduction and enactment—introducing thresholds, constraints, or material forms that stabilize state transitions. At the computing level, systems can be strengthened by incorporating redundancy and contextual reasoning: combining multiple sensing channels or multiple placements to reduce uncertainty; exploiting materials that support multimodal transduction (e.g., simultaneously producing optical and electrical cues [62]) to provide complementary evidence. As computational methods evolve, an additional direction is to shift part of the interpretation burden from purely pattern-based classification toward context-informed reasoning—where signals are interpreted in relation to task, setting, and plausible action sequences that are potentially enabled by recent progress in large language models [12, 29]. The broader implication is that making material-mediated sensing usable in practice may depend as much on designing interpretative scaffolding as on designing the sensing material itself.

Embodied variability. AMES interfaces are enacted through practice: signals depend on how people touch, press, stretch, or inhabit materials. This creates opportunities for expressive, skillful interaction, yet it also makes sensing sensitive to individual differences, learned routines, and shifts in posture or technique [9, 50]. A central challenge is that the same material affordances that invite rich engagement can also widen the space of possible actions. Designers may need to deliberately choreograph enactment—using thresholds, guidance, and constraints, so that embodied interaction remains interpretable without reducing it to a single "correct" gesture.

Interpretation cost and lifecycle. Finally, material-mediated sensing often shifts labor from hardware assembly to interpretation and maintenance. Systems may require calibration, personalization, or periodic re-training as materials age, are repositioned, or are deployed in new environments. This lifecycle burden is easy to underestimate because it emerges after prototyping, during real use [35, 52]. From an AMES perspective, interpretation is not merely a downstream computational step but part of the sensing arrangement that must be designed and sustained. This motivates research directions in robust inference, transferable representations across materials, and interaction techniques that make calibration and repair part of everyday practice rather than an exceptional engineering task.

6.4 Edges and Limits of AMES

Because AMES foregrounds sensing as constituted through material behavior, it is most generative when material change can reliably mediate between action in the world and interpretation by a system. This suggests a practical heuristic for scope: *AMES applies best when (1) material change is coupled to meaningful actions or events, (2) that change can be made legible to users or to the environment, and (3) it can be interpreted with tolerable ambiguity under realistic conditions.* When these conditions do not hold, material-mediated sensing may still be possible, but it becomes harder to design for robustness, understandability, and long-term deployment. Additionally, it's worth mentioning that while AMES treats materials as an active substrate of sensing, not every interactive artifact involving *materials* meaningfully instantiates material-embodied sensing.

Non-AMES cases include systems where the material is primarily a cosmetic cover or ergonomic enclosure while the sensing is fully determined by conventional, encapsulated sensors. Likewise, systems that rely on an external instrument as the primary sensing substrate—such as camera—centric tracking of a deformable surface where the material only serves as a visual target, may benefit from material expressivity but do not foreground the material as the transducer itself. Another closely related example arises in wireless sensing (e.g., mmWave radar- or Wi-Fi-based sensing). Many such systems operate by treating the environment and the human body as scatterers within an instrumented electromagnetic field [34]. In this sensor-centric configuration, the locus of transduction remains within the encapsulated sensing apparatus rather than being externalized into a *designed material substrate*, and thus these systems typically fall outside the analytical focus of AMES. However, AMES may become relevant at the boundary when engineered structures or media are intentionally designed to *materialize* wave interactions—e.g., by shaping waveguiding, resonance, attenuation, or scattering patterns—so that part of the sensing function is effectively delegated to physical configurations that can be reasoned about as a sensing medium [2, 26].

One way to reason about these edges is through four criteria. First, **temporal bandwidth**: some material phenomena evolve too slowly, too diffusely, or with long recovery times for interactive use. Thermal and many chemical processes, for example, can be highly informative but may introduce latency and hysteresis that make moment-to-moment interaction difficult, especially when the same material simultaneously accumulates environmental history [5, 16, 45]. Second, **controllability**: AMES is more effective when designers can shape how a material responds—through morphology, constraints, placement, or boundary conditions—so that interaction produces consistent and discriminable changes. Phenomena dominated by uncontrolled diffusion or turbulence can be expressive, yet often require substantial inference to stabilize [35, 36].

Third, **separability from ambient confounds**: material-mediated sensing becomes fragile when the relevant signal is strongly entangled with environmental variation that cannot be measured or modeled. Optical transduction, for instance, can be powerful when light transport is structured by material morphology, but it becomes harder to interpret when illumination changes unpredictably or when occlusion is unaccounted for [51, 52]. Finally, **legibility to users**: AMES is most aligned with interaction design when material change supports a comprehensible action-effect relation—something users can feel, see, or anticipate—rather than producing effects that are only discoverable through system feedback. Legibility is not a requirement for all sensing systems, but it shapes whether material-mediated sensing can support learnable and explainable interaction.

Importantly, these limits are not exclusions but design pressures. They help explain why some modalities demand heavier ambient inference, stronger redundancy, or explicit calibration practices, and why certain material choices yield interfaces that are *compelling as demonstrations yet difficult to sustain in everyday settings.* By making these pressures explicit, AMES aims to support more deliberate material selection and sensing design, clarifying when material-mediated sensing is a good fit, and what additional scaffolding is required when it is not.

6.5 Implications for the HCI Research Ecosystem

Material-mediated sensing has become a prolific site of invention in HCI, yet much of this work remains difficult to sustain beyond demonstrations—a pattern that resonates with broader concerns around replicability and cumulative knowledge in the field [6, 59]. Many systems are evaluated in controlled setups with carefully prepared materials, constrained interactions, and limited environmental variability; practical deployment concerns—drift, fabrication inconsistency, maintenance, calibration, and cross-context transfer—are often acknowledged but deferred as limitations. This pattern is understandable: Technical characterizations centered on materials, fabrication procedures, and sensing performance can be reported with relatively clear setups and measurable outcomes [35, 56], whereas more abstract interaction or material principles as well as the open-ended questions about how practices form, stabilize, and extend beyond contexts are harder to substantiate without solid evidence. As a result, accounts of interaction and use are often presented conservatively in discussion. When these constraints remain unaddressed, the field risks accumulating compelling one-off artifacts without a commensurate accumulation of reusable knowledge about why they work, when they fail, and how they can be adapted [18].

AMES is introduced with the motivation to support HCI's longer-lasting intellectual heritage by offering an integrative lens for a line of research that is currently rich in invention but fragmented in conceptual articulation [10, 41]. It encourages reporting *mechanisms* along with the artifacts or devices: making explicit how transduction is realized in the material system, how enactment is shaped through coupling, and what contextual assumptions inference relies on; it foregrounds *lifecycle* as a design concern: documenting how signals change with wear, repositioning, environmental shifts, and fabrication variance, and treating calibration and repair as part of the interaction rather than purely an engineering afterthought; it motivates *comparability and composition*: if systems can be described through shared mechanisms, researchers can more plausibly compare approaches, reason about redundancy, and build toward multi-material ecosystems. More broadly, these moves aim to support a more cumulative research trajectory, where contributions can be situated not only by what artifacts demonstrate, but by how sensing is constituted and sustained in practice under material and contextual variability.

7 Future Work

On Evaluation and Validation. As a theoretical framework, AMES is unlikely to be assessed through a single, self-contained study; its validation is inherently longer-term and depends on how the community adopts, tests, and revises its concepts in diverse settings. This paper takes a retrospective stance: we synthesize recurring patterns across prior material-mediated sensing systems and consolidate them into the AMES framework. Within this scope, we focus on establishing (i) *conceptual validity*, by articulating a coherent set of mechanisms and clarifying edges and limits, and (ii) *analytical utility*, by demonstrating how AMES supports systematic reinterpretation and comparison across heterogeneous exemplars. Questions about whether and how AMES improves design outcomes may be examined prospectively—for instance through interviews, design workshops, or studies that apply AMES during the creation of new systems. Such evaluations are beyond the scope of this paper but would remain important directions for future work.

From Conceptual Framework to Design Guidance. While we articulate design implications in Section 6.2, their role in this paper is not to prescribe a fully operational design method, but to serve as an initial step toward a more structured understanding of material-mediated sensing. Developing a rigorous design guideline would likely require more controlled formulations and systematic validation than is appropriate at this stage. Future work may therefore explore how the conceptual distinctions introduced by AMES can be translated into more stable yet flexible forms of guidance, such as design heuristics or intermediate representations. Such efforts may remain attentive to the diversity and contingency of material behaviors, where choices of materials, configurations, and contexts resist reduction to fixed procedures.

8 Conclusion

This paper introduced Ambient Material-Embodied Sensing (AMES) as a design-theoretical framework for articulating sensing as an emergent process grounded in material transduction, enacted by Embodied Coupling, and made actionable through ambient inference. We first motivated AMES through recurring observations of how materials reshape sensing modalities, extend sensing scope, offload complexity, and become implicitly embedded in inference. We then situated AMES within prior HCI accounts of materiality, embodied interaction, and ubiquitous/context-aware systems, showing how these traditions collectively background sensing even as practice increasingly depends on it. Finally, we demonstrated AMES as an analytical lens by reinterpreting twelve representative systems through a transduction-oriented taxonomy, and we discussed design opportunities, trade-offs, and limits that arise when sensing is delegated to material behavior in real settings. By making the material constitution of sensing explicit, we hope this framework provides a shared conceptual foundation for the HCI community to critically design, compare, and sustain the next generation of material-mediated interactive systems.

Acknowledgments

This work was supported by JST Keio-SPRING (Grant Number Y01GQ25160), JST AIP Acceleration Research (Grant Number JP-MJCR25U4), and JSPS KAKENHI (Grant Number JP25K03168). Ken-Tye Yong gratefully acknowledge the support of the Keio University Global Faculty Program (Guest Professor (Global) Program), which enabled international collaborative research and co-authorship activities. This work was also supported by the Net Zero Institute Impact Award (Grant Number RV455), which facilitated this research collaboration.

References

[1] Imtiaz Ahmad, Rosta Farzan, Apu Kapadia, and Adam J. Lee. 2020. Tangible Privacy: Towards User-Centric Sensor Designs for Bystander Privacy. *Proc. ACM Hum.-Comput. Interact.* 4, CSCW2, Article 116 (Oct. 2020), 28 pages. doi:10.1145/3415187

[2] Marwa AlAlawi, Regina Zheng, Sooyeon Ahn, Katherine Yan, Ticha Sethapakdi, Junyi Zhu, and Stefanie Mueller. 2025. Demonstration of Meta-antenna: Mechanically Frequency Reconfigurable Metamaterial Antennas. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST Adjunct '25).* Association for Computing Machinery, New York, NY, USA, Article 28, 5 pages. doi:10.1145/3746058.3758991

[3] Brian Amento, Will Hill, and Loren Terveen. 2002. The sound of one hand: a wrist-mounted bio-acoustic fingertip gesture interface. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems* (Minneapolis, Minnesota, USA) *(CHI EA '02).* Association for Computing Machinery, New York, NY, USA, 724–725. doi:10.1145/506443.506566

[4] Jenny Bergström, Brendon Clark, Alberto Frigo, Ramia Mazé, Johan Redström, and Anna Vallgårda. 2010. Becoming materials: Material forms and forms of practice. *Digital Creativity* 21 (09 2010), 155–172. doi:10.1080/14626268.2010.502235

[5] Ayush Bhardwaj, Ashish Pratap, Abbas Khawaja, Yatharth Singhal, Hyunjae Gil, and Jin Ryong Kim. 2025. Understanding Latency Sensitivity in Thermal and Tactile Feedback for Multimodal Haptics in VR. In *Proceedings of the 2025 31st ACM Symposium on Virtual Reality Software and Technology (VRST '25).* Association for Computing Machinery, New York, NY, USA, Article 53, 11 pages. doi:10.1145/3756884.3766050

[6] Andy Cockburn, Pierre Dragicevic, Lonni Besançon, and Carl Gutwin. 2020. Threats of a replication crisis in empirical computer science. *Commun. ACM* 63, 8 (July 2020), 70–79. doi:10.1145/3360311

[7] Youngwook Do, Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Eryue Xu, Zhihan Zhang, Gregory D. Abowd, and Sauvik Das. 2023. Powering for Privacy: Improving User Trust in Smart Speaker Microphones with Intentional Powering and Perceptible Assurance. In *32nd USENIX Security Symposium (USENIX Security 23).* USENIX Association, Anaheim, CA, 2473–2490. https://www.usenix.org/conference/usenixsecurity23/presentation/do

[8] Tanja Döring. 2016. The Interaction Material Profile: Understanding and Inspiring How Physical Materials Shape Interaction. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16).* Association for Computing Machinery, New York, NY, USA, 2446–2453. doi:10.1145/2851581.2892516

[9] Paul Dourish. 2001. *Where the Action Is: The Foundations of Embodied Interaction.* MIT Press, Cambridge, MA.

[10] Florian Echtler and Maximilian Häußler. 2018. Open Source, Open Science, and the Replication Crisis in HCI. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18).* Association for Computing Machinery, New York, NY, USA, 1–8. doi:10.1145/3170427.3188395

[11] Willemijn S. Elkhuizen, Jeff Love, Stefano Parisi, and Elvin Karana. 2024. On the Role of Materials Experience for Novel Interactions with Digital Representations of Historical Pop-up and Movable Books. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 619, 18 pages. doi:10.1145/3613904.3642142

[12] Michele Fiori, Gabriele Civitarese, Priyankar Choudhary, and Claudio Bettini. 2025. Leveraging Large Language Models for Explainable Activity Recognition in Smart Homes: A Critical Evaluation. *ACM Trans. Internet Things* 6, 4, Article 24 (Nov. 2025), 25 pages. doi:10.1145/3766900

[13] Yibo Fu, Vivian Shen, Víctor Riera Naranjo, Bolei Deng, Alex Adams, and Josiah Hester. 2025. SoundOff: Low-cost Passive Ultrasound Tags for Non-invasive and Non-Intrusive Smart Home Sensing. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 9, 4, Article 174 (Dec. 2025), 32 pages. doi:10.1145/3770666

[14] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2447–2456. doi:10.1145/2702123.2702337

[15] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1063–1073. doi:10.1145/3472749.3474806

[16] Eduard Georges Groutars, Carmen Clarice Risseeuw, Colin Ingham, Raditijo Hamidjaja, Willemijn S. Elkhuizen, Sylvia C. Pont, and Elvin Karana. 2022. Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 99, 19 pages. doi:10.1145/3491102.3517713

[17] K. Hara. 2007. *Designing Design.* Lars M\AN232uller. https://books.google.co.jp/books?id=A0RJAQAAIAAJ

[18] Kasper Hornbæk, Søren S. Sander, Javier Andrés Bargas-Avila, and Jakob Grue Simonsen. 2014. Is once enough? on the extent and content of replications in human-computer interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3523–3532. doi:10.1145/2556288.2557004

[19] Eva Hornecker and Jacob Buur. 2006. Getting a grip on tangible interaction: a framework on physical space and social interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 437–446. doi:10.1145/1124772.1124838

[20] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '97)*. Association for Computing Machinery, New York, NY, USA, 234–241. doi:10.1145/258549.258715

[21] Mads Vedel Jensen, Jacob Buur, and Tom Djajadiningrat. 2005. Designing the user actions in tangible interaction. In *Proceedings of the 4th Decennial Conference on Critical Computing: Between Sense and Sensibility* (Aarhus, Denmark) *(CC '05)*. Association for Computing Machinery, New York, NY, USA, 9–18. doi:10.1145/1094562.1094565

[22] Elvin Karana, Paul Hekkert, and Prabhu Kandachar. 2008. Materials experience: Descriptive categories in material appraisals. *Proceedings of TMCE 2008 Symposium.*

[23] Kaho Kato, Kohei Matsumura, and Yuta Sugiura. 2019. AroundSense: An Input Method for Gestures around a Smartphone. *Proceedings of the International Display Workshops* (11 2019), 1700. doi:10.36463/idw.2019.1700

[24] Stacey Kuznetsov and Eric Paulos. 2010. Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (Reykjavik, Iceland) *(NordiCHI '10)*. Association for Computing Machinery, New York, NY, USA, 295–304. doi:10.1145/1868914.1868950

[25] Gierad Laput. 2019. Context-driven Implicit Interactions. *Doctoral Dissertation* (2019). http://reports-archive.adm.cs.cmu.edu/anon/hcii/CMU-HCII-19-103.pdf

[26] Gierad Laput, Eric Brockmeyer, Scott E. Hudson, and Chris Harrison. 2015. Acoustruments: Passive, Acoustically-Driven, Interactive Controls for Handheld Devices. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2161–2170. doi:10.1145/2702123.2702414

[27] Gierad Laput, Robert Xiao, and Chris Harrison. 2016. ViBand: High-Fidelity Bio-Acoustic Sensing Using Commodity Smartwatch Accelerometers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 321–333. doi:10.1145/2984511.2984582

[28] Gierad Laput, Yang Zhang, and Chris Harrison. 2017. Synthetic Sensors: Towards General-Purpose Sensing. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3986–3999. doi:10.1145/3025453.3025773

[29] Zikang Leng, Megha Thukral, Yaqi Liu, Hrudhai Rajasekhar, Shruthi K. Hiremath, Jiaman He, and Thomas Plötz. 2025. AgentSense: Virtual Sensor Data Generation Using LLM Agents in Simulated Home Environments. arXiv:2506.11773 [cs.CV] https://arxiv.org/abs/2506.11773

[30] Xin Liu, Chengkuo Lee, Clement Zheng, and Ching Chiuan Yen. 2025. Designing Physical Interactions with Triboelectric Material Sensing. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 683, 20 pages. doi:10.1145/3706598.3714194

[31] Xin Liu, Chengkuo Lee, Clement Zheng, and Ching Chiuan Yen. 2025. Designing Physical Interactions with Triboelectric Material Sensing. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 683, 20 pages. doi:10.1145/3706598.3714194

[32] Lian Loke and Toni Robertson. 2013. Moving and making strange: An embodied approach to movement-based interaction design. *ACM Trans. Comput.-Hum. Interact.* 20, 1, Article 7 (April 2013), 25 pages. doi:10.1145/2442106.2442113

[33] Vikram Mehta, Daniel Gooch, Arosha Bandara, Blaine Price, and Bashar Nuseibeh. 2021. Privacy Care: A Tangible Interaction Framework for Privacy Management. *ACM Trans. Internet Technol.* 21, 1, Article 25 (Feb. 2021), 32 pages. doi:10.1145/3430506

[34] Fucheng Miao, Youxiang Huang, Zhiyi Lu, Tomoaki Ohtsuki, Guan Gui, and Hikmet Sari. 2025. Wi-Fi Sensing Techniques for Human Activity Recognition: Brief Survey, Potential Challenges, and Research Directions. *ACM Comput. Surv.* 57, 5, Article 107 (Jan. 2025), 30 pages. doi:10.1145/3705893

[35] Tian Min, Yuma Tsukakoshi, Chengshuo Xia, Anusha Withana, and Yuta Sugiura. 2025. SoilSense: Appropriating Soil-based Microbial Fuel Cells to Create Tangible Interfaces. In *Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25)*. Association for Computing Machinery, New York, NY, USA, Article 38, 15 pages. doi:10.1145/3746059.3747675

[36] Tian Min, Chengshuo Xia, Takumi Yamamoto, and Yuta Sugiura. 2023. Seeing the Wind: An Interactive Mist Interface for Airflow Input. *Proc. ACM Hum.-Comput. Interact.* 7, ISS, Article 444 (Nov. 2023), 22 pages. doi:10.1145/3626480

[37] Yamato Miyatake and Parinya Punpongsanon. 2025. An Exploratory Study on Edible Conductive Materials Using Water and Oil-based Gels for Human-Food Interaction. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST Adjunct '25)*. Association for Computing Machinery, New York, NY, USA, Article 129, 3 pages. doi:10.1145/3746058.3758423

[38] Satoshi Nakamaru, Ryosuke Nakayama, Ryuma Niiyama, and Yasuaki Kakehi. 2017. FoamSense: Design of Three Dimensional Soft Sensors with Porous Materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 437–447. doi:10.1145/3126594.3126666

[39] Hye Yeon Nam, JaNiece Campbell, Andrew M. Webb, and Brendan Harmon. 2023. FloraWear: Wearable Living Interface. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 30, 15 pages. doi:10.1145/3569009.3572801

[40] Madalina Nicolae. 2025. Rethinking the Fabrication of Interactive Devices Through Biomaterials: Towards New Paradigms of Making and Materiality in HCI. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST Adjunct '25)*. Association for Computing Machinery, New York, NY, USA, Article 9, 5 pages. doi:10.1145/3746058.3758465

[41] Jonas Oppenlaender and Simo Hosio. 2025. Keeping Score: A Quantitative Analysis of How the CHI Community Appreciates Its Milestones. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 452, 17 pages. doi:10.1145/3706598.3713464

[42] Siyou Pei, Pradyumna Chari, Xue Wang, Xiaoying Yang, Achuta Kadambi, and Yang Zhang. 2022. ForceSight: Non-Contact Force Sensing with Laser Speckle Imaging. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 25, 11 pages. doi:10.1145/3526113.3545622

[43] Rosalind W. Picard. 1997. *Affective computing.* MIT Press, Cambridge, MA, USA.

[44] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–23. doi:10.1145/3173574.3173948

[45] Juhi Ranjan and James Scott. 2016. ThermalSense: determining dynamic thermal comfort preferences using thermographic imaging. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Heidelberg, Germany) *(UbiComp '16)*. Association for Computing Machinery, New York, NY, USA, 1212–1222. doi:10.1145/2971648.2971659

[46] Tomoya Sasaki, MHD Yamen Saraiji, Charith Lasantha Fernando, Kouta Minamizawa, and Masahiko Inami. 2017. MetaLimbs: multiple arms interaction

metamorphism. In *ACM SIGGRAPH 2017 Emerging Technologies* (Los Angeles, California) *(SIGGRAPH '17)*. Association for Computing Machinery, New York, NY, USA, Article 16, 2 pages. doi:10.1145/3084822.3084837

[47] R. Sennett. 2008. *The Craftsman.* Yale University Press. https://books.google.co.jp/books?id=SRAV0KvuOQwC

[48] Fereshteh Shahmiri, Chaoyu Chen, Anandghan Waghmare, Dingtian Zhang, Shivan Mittal, Steven L. Zhang, Yi-Cheng Wang, Zhong Lin Wang, Thad E. Starner, and Gregory D. Abowd. 2019. Serpentine: A Self-Powered Reversibly Deformable Cord Sensor for Human Input. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3290605.3300775

[49] Ronit Slyper, Ivan Poupyrev, and Jessica Hodgins. 2010. Sensing through structure: designing soft silicone sensors. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 213–220. doi:10.1145/1935701.1935744

[50] Lucy A. Suchman. 1987. *Plans and situated actions: the problem of human-machine communication.* Cambridge University Press, USA.

[51] Yuta Sugiura, Masahiko Inami, and Takeo Igarashi. 2012. A thin stretchable interface for tangential force measurement. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology* (Cambridge, Massachusetts, USA) *(UIST '12)*. Association for Computing Machinery, New York, NY, USA, 529–536. doi:10.1145/2380116.2380182

[52] Yuta Sugiura, Gota Kakehi, Anusha Withana, Calista Lee, Daisuke Sakamoto, Maki Sugimoto, Masahiko Inami, and Takeo Igarashi. 2011. Detecting shape deformation of soft objects using directional photoreflectivity measurement. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology* (Santa Barbara, California, USA) *(UIST '11)*. Association for Computing Machinery, New York, NY, USA, 509–516. doi:10.1145/2047196.2047263

[53] Yuma Tsukakoshi, Tian Min, Annemarie Spiller, Chengshuo Xia, Anusha Withana, and Yuta Sugiura. 2025. SoilTile: Soil-based Ground Sensing. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST Adjunct '25)*. Association for Computing Machinery, New York, NY, USA, Article 164, 3 pages. doi:10.1145/3746058.3758371

[54] Jelle van Dijk, Remko van der Lugt, and Caroline Hummels. 2014. Beyond distributed representation: embodied cognition design supporting socio-sensorimotor couplings. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 181–188. doi:10.1145/2540930.2540934

[55] Guanyun Wang, Humphrey Yang, Zeyu Yan, Nurcan Gecer Ulu, Ye Tao, Jianzhe Gu, Levent Burak Kara, and Lining Yao. 2018. 4DMesh: 4D Printing Morphing Non-Developable Mesh Surfaces. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 623–635. doi:10.1145/3242587.3242625

[56] Keisuke Watanabe, Ryosuke Yamamura, and Yasuaki Kakehi. 2021. foamin: A Deformable Sensor for Multimodal Inputs Based on Conductive Foam with a Single Wire. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 189, 4 pages. doi:10.1145/3411763.3451547

[57] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2991–3000. doi:10.1145/2702123.2702391

[58] Mark Weiser. 1999. The computer for the 21st century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (July 1999), 3–11. doi:10.1145/329124.329126

[59] Max L. Wilson, Ed H. Chi, Stuart Reeves, and David Coyle. 2014. RepliCHI: the workshop II. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI EA '14)*. Association for Computing Machinery, New York, NY, USA, 33–36. doi:10.1145/2559206.2559233

[60] Sang Ho Yoon, Luis Paredes, Ke Huo, and Karthik Ramani. 2018. MultiSoft: Soft Sensor Enabling Real-Time Multimodal Sensing with Contact Localization and Deformation Classification. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 145 (Sept. 2018), 21 pages. doi:10.1145/3264955

[61] Takatoshi Yoshida, Narin Okazaki, Ken Takaki, Masaharu Hirose, Shingo Kitagawa, and Masahiko Inami. 2022. Flexel: A Modular Floor Interface for Room-Scale Tactile Sensing. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 24, 12 pages. doi:10.1145/3526113.3545699

[62] Dingtian Zhang, Jung Wook Park, Yang Zhang, Yuhui Zhao, Yiyang Wang, Yunzhi Li, Tanvi Bhagwat, Wen-Fang Chou, Xiaojia Jia, Bernard Kippelen, Canek Fuentes-Hernandez, Thad Starner, and Gregory D. Abowd. 2020. OptoSense: Towards Ubiquitous Self-Powered Ambient Light Sensing Surfaces. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3, Article 103 (Sept. 2020), 27 pages. doi:10.1145/3411826

[63] Yang Zhang and Chris Harrison. 2015. Tomo: Wearable, Low-Cost Electrical Impedance Tomography for Hand Gesture Recognition. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 167–173. doi:10.1145/2807442.2807480

[64] Yang Zhang, Chouchang (Jack) Yang, Scott E. Hudson, Chris Harrison, and Alanson Sample. 2018. Wall++: Room-Scale Interactive and Context-Aware Sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3173574.3173847