

Lumora Cards: An Annotated Portfolios-Based Design Tool to Support Novice Designers in Integrating Smart Materials into Interactive Physicalization

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ABSTRACT

Smart materials have been widely studied for interactive physicalization, yet novice designers lack support in integrating them effectively. This study introduces Lumora Cards, a tangible interface combining physical material samples with annotated portfolio guidance to facilitate heuristic exploration. The cards map 180 design elements across five stages, enabling context-appropriate material selection. In a 12-day workshop with 32 novices, quantitative results showed that Lumora Cards significantly enhanced creativity, confidence, and perceived usefulness. Qualitative findings provided actionable methods for workflow integration. This work offers both a theoretical framework and practical tools for applying smart materials in interactive physicalization design.

Keywords: Exemplary interactive physicalization, Smart materials, Tangible embodied interface, Card-based design tools, Workshops, APM analysis

INTRODUCTION

Physicalization involves representing and interacting with abstract data through physical entities (Bae et al., 2022). As the field shifts from static mapping to dynamic systems, Interactive Physicalization (IP) has attracted increasing interest in domains such as personal health and public communication. In IP, Smart Materials (SMs) serve as dynamic mediators between data and user perception (Ding et al., 2024), transforming abstract information into tangible, changeable forms (Ding et al., 2024) and supporting real-time bidirectional interaction (Hogan & Hornecker, 2013). Composed of environment-responsive units, SMs encode data directly through their dynamic properties, enabling real-time expression and enriched interaction (Ke et al., 2023). Although prior work (Boem & Iwata, 2018)

(Minuto & Pittarello, 2015) has employed SMs as tangible interfaces for data visualization, few studies have focused on bridging theory and practice for novice designers or on systematically integrating multidisciplinary knowledge through hands-on material exploration.

Despite their potential, applying SMs in IP heavily depends on designers' intuitive grasp of material-data relationships (Hurtienne et al., 2020), which poses a significant challenge for novices (Lin & Lu, 2024). Existing research often prioritizes technical implementation over systematizing two key issues: lowering the learning barrier via design tools, and operationalizing embodied SM experiences (e.g., haptics (Sauvé et al., 2024), shape-change (Ding et al., 2024)) for data-expression goals.

To address this gap, we propose Lumora framework and card tools based on the annotated portfolio methodology hh(APM) (Gaver & Boucher, 2024). The reason we use APM is that moving beyond literature reviews often limited to abstract theories (Bae et al., 2022) (Ranasinghe & Degbelo, 2023). In our study, we reconcile abstract principles (e.g., material responsiveness (Delany et al., 2012)) with concrete design cases (Boem & Iwata, 2018) (Minuto & Pittarello, 2015) through a process of theory→case validation→pattern extraction. This forms the basis of our first research question:

RQ1: How to systematize SMs integration into IP design using APM?

Building on APM, we developed Lumora Cards to guide SMs application in IP. Unlike conventional card-based tools (Halskov & Dalsgård, 2006) (Hsieh et al., 2023), Lumora Cards integrate a hierarchical theoretical framework with embedded physical SM samples, encoding meta-rules as actionable design elements while providing tangible references for multimodal interaction. This leads to our second question:

RQ2: Whether and how does the Lumora Cards support novice designers in leveraging SMs to achieve IP?

We conducted a between-group workshop experiment. Results from eight novel design concepts, supported by quantitative and qualitative data, confirmed that the APM-based tool enhanced novices' understanding of IP principles, improved SM application skills, and fostered creative material integration.

Our contributions are: (1) exploring the effectiveness of APM-based card tools for IP design; (2) proposing a novel tool that integrates SM samples with cards to guide novices; (3) empirically validating Lumora's guidance through a card-based design process, contributing to the development of SM-enabled IP design tools.

METHODOLOGY

Four guiding principles underpinned the framework's development using APM:

- (1) **Indexicality:** Design knowledge is derived from concrete cases and shared accessibly, using visual formats and tangible material samples.
- (2) **Process Support:** The tool provides a coherent framework guiding participants through all workshop phases.

- (3) **Open-Endedness:** Prompts are problem-oriented, incorporating blank areas and multiple-choice options to stimulate divergent thinking.
- (4) **Layered Annotation:** A three-tier structure (foundational workflow, explanatory knowledge with materials, and extended guidance) offers structured yet flexible scaffolding.

Our framework development followed three key steps:

- (1) **Case Collection & Categorization:** We collected and analyzed 30 peer-reviewed cases on smart material-data integration, tagging recurring patterns.
- (2) **Hierarchical Annotation:** Cross-case strategies were identified, innovative approaches distilled, and actionable workflows formalized into a tiered framework.
- (3) **Pilot Validation:** Experts evaluated the framework’s practicality by applying it to a “natural interaction” theme, leading to iterative refinements.

Through APM analysis, we categorized the framework into five dimensions: Design Position, Data, Material, Sense, and Interaction (Figure 1). This structure is non-linear, allowing users to move fluidly between categories to refine their design approach. When using it, users can also flexibly move between, combine, and iteratively adjust the above five dimensions to refine their approach.

Design categories, sub-categories and keywords in Lumora Cards			Design categories, sub-categories and keywords in Lumora Cards			
	sub-categories	Keywords	Dimensions	Elements		
DESIGN POSITION	Audience	General Public, Semi-Public, Private, Imperfect Groups, Specific Groups, Others	Kinesthetic	Kinesthetic location, Motion, Speed, Inertia, Weight, Kinesthetic force, Kinesthetic friction, viscosity	SENSE	
	Usage scenario	Indoors, Outdoors, Unspecified, Others	Synesthesia	Combination of two senses, Combination of three senses, Combination of four senses, Combination of five senses		
	Theme	Sports, Health, Fashion	Aural	Sound source location, Loudness, Pitch, Register, Timbre, Rhythmic Patterns, Duration, Envelope, Melody		
	Intent	Analysis, Educate, Express, Enjoy, Reflect, Encouraging Sustainability, Discovery of Information, Unspecified, Others	Taste	Taste type, temperature of the taste carrier		
	Data Availability	Static, Dynamic	Olfactory	Scant type, Scant direction, Scant saturation, Air flow rate, Air quality		
	Data Attributes	Ordinal Data, Categorical Data, Quantitative Data, Qualitative Data, Other	Dynamic	Persistence time, Temporal order, Duration, Temporal frequency, Rate of change, Synchronization, Change pattern		
DATA	Data Source	Biological and Medical Data, General Statistics Data, General Statistics Data, General Statistics Data, Geographical Data, Environmental Data, Social Media Data, Social Media Data, Social Media Data, Other	Balance	Static equilibrium, Dynamic balance, Dynamic balance, Muscle balance, Psychological balance	INTERACTION	
	MATERIAL	Intelligent Material Type	Optical fiber and optical fiber sensor, Shape memory materials, Piezoelectric materials, Photodegradable materials, Electrodegenerative material, Magnetotropic material, Other	Spaciousness		Sense of distance, Sense of direction
		Material Properties	Physical property, Chemical property, Mechanical property, Thermal property, Optical property, Biocompatibility, Other	Sense of time		Sense of short time, Sense of long time
		Usage Characteristics	Elasticity, Aesthetics, Adjustable, Foldable, Inflatable, Anisotropic, Multi-stable, Shape memory	Sense of temperature		Happiness, Comfort perception
Material template	Conductive tape, Conductive tape, Graphene ultra-thin conductive material, Optical fiber, Soft magnet, Variable Ink, Magneto fluid, Memory metal	Interaction Mediator	Materials, Sensed, None, Others			
SENSE	Visual	Visual location, Colour hue, Colour value, Colour saturation, Visual size, Visual shape, Visual orientation, Visual arrangement, Visual texture, Clarity, Resolution, Visual transparency, Light, Movement/Action, Timing	Interaction mode	Explore, Reconfigure, Encode, Abstract, Filter, Connect, Annotate, Collect, Assemble		
	Tactile	Tangible size, Temperature, Tangible texture, 3D-form/Contour, Compliance, Vibration Force, Vibration amplitude, Vibration frequency, Pressure/Force-strengths, Resistance, Friction, Tangible elevation, Tangible shape, Tangible orientation, Tangible location, Tangible arrangement, Tangible numeroseness				

Figure 1: The overview of the design framework.

THE WORKSHOP

To evaluate the framework’s efficacy, we implemented it through Lumora card-based design tool, which integrates tangible SMs samples. A between-subjects experiment was conducted to examine the impact of the tool and address RQ1 and RQ2. This led to two research hypotheses:

- H1: The APM framework fosters significant creativity in IP utilizing SMs.
- H2: Incorporating hands-on SMs samples as experiential TEI cards results is effective in IP design.

The Tools of the Workshop

The Lumora Cards

The framework is presented to users through Lumora Cards (Figure 4), designed for clarity and ease of use. The cards are organized into five color-coded categories: DESIGN POSITION (purple), DATA (pink), MATERIAL (yellow), SENSE (blue), and INTERACTION (green).

- (1) **Description Cards** include visual references, textual explanations, and reflection areas.
- (2) **Sticky Cards** incorporate a section for attaching physical SM samples, allowing tactile exploration of material properties (Figure 2). Materials that were difficult to source, fabricate, or posed safety risks were excluded.
- (3) **Tick-Box Cards** offer quick selection options for categorical elements.

All cards feature a front-side image corresponding to the card name, with uniform dimension information on the back. DESIGN POSITION cards include blank areas for user notes. DATA cards focus on data characteristics. MATERIAL cards comprise both Description and Sticky types, supplemented with a blank template card and introductory case studies to encourage creative exploration without constraint. SENSE cards cover 13 sub-categories, many with tick-box options for sensory aspects. INTERACTION cards guide consideration of product-user interaction. Each category also provides an “other” card for users to note additional ideas not included in the set.

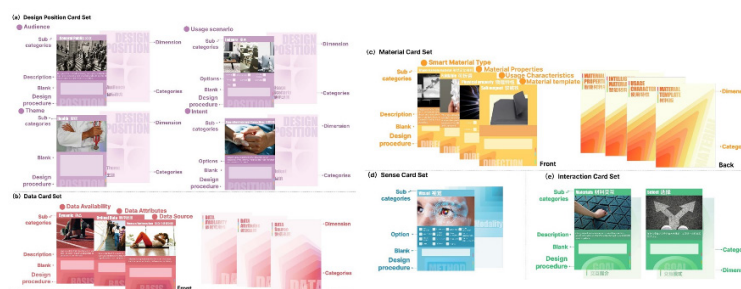


Figure 2: The types of the Lumora cards. (a) Description Card. (b) Sticky Card. (c) Tick Box Card.

3.1.2 The Lumora Canvas

To standardize card use, we developed a structured canvas that scaffolds the design process. The canvas organizes the five card categories and includes a dedicated area for articulating design thinking (Figure 3). Designed to be used sequentially with the playbook, it allows participants to place selected

cards in “The card placement area” and subsequently describe their design concepts in “The design specification area.”



Figure 3: The overview of the canvases.

Participants

We recruited 32 design students (8 males, 24 females; age $M = 22.63$, $SD = 2.11$) through online outreach. All participants had at least one year of design experience and basic knowledge of design methods. Using a 5-point Likert scale (1 = inexperienced, 5 = experienced), their self-reported expertise was confirmed novice status in both smart materials ($M = 1.5$, $SD = 0.5$) and interactive physicalization design ($M = 1.47$, $SD = 0.34$). Informed consent was obtained prior to the experiment, with participants allowed to withdraw at any time. No monetary compensation was provided, though they could keep their prototypes. Participants self-organized into 8 groups (G1–G8) of at least two members each, with G1–G4 assigned to the experimental group (EP1–EP16) and G5–G8 to the control group (CP17–CP32).

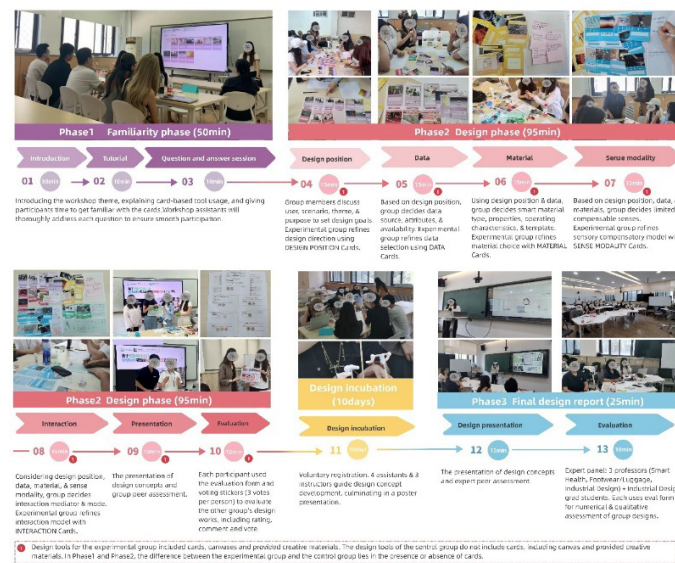


Figure 4: Workshop procedure.

Workshop Procedure

As shown in Figure 4, the workshop comprised three phases, each with identical steps for the experimental group (with Lumora cards) and the control group (without cards).

Phase 1: Familiarity

A 40-minute pre-workshop orientation introduced the theme “Fashion Design of Sports Products in the Context of General Health,” structured as a 20minute introduction, 10minute tutorial, and 10minute Q&A.

Phase 2: Design

This 3-hour session began with tool distribution. The experimental group used Lumora cards with a canvas and materials, while the control group worked with only the canvas and materials. Groups then conducted 15-minute ideation for each of the five categories, followed by presentations, peer evaluation, and prototype creation, where interested groups further refined their prototypes and posters with researcher guidance within a 10-day incubation period.

Phase 3: Final Design Report

Each group gave a 15-minute presentation of their design concepts in dedicated spaces. Three professors from School of Fashion Accessory, Beijing Institute of Fashion Technology evaluated via expert forms, scoring material selection appropriateness, multisensory data mapping effectiveness and interaction novelty, and providing written feedback.

Data Collection and Analysis

Quantitative data were collected through pre- and post-workshop surveys. We adapted Bandura’s self-efficacy framework (Bandura, 2022) with nine items (scale 0–100) measuring confidence in building IP prototypes with SMs. Perceived usefulness and ease of use were assessed via a seven-point Likert scale (He et al., 2018) (Zhang et al., 2023). Post-workshop creativity was evaluated using the Creativity Support Index (CSI) (Carroll & Latulipe, 2009) . As data violated normality (Shapiro–Wilk, $p < .05$), nonparametric tests were applied in SPSS.

Qualitative data included semistructured interviews conducted after Phase 2, focusing on participants’ views of the framework, tools, workshop experience, and SM application in IP. All interviews were recorded and transcribed. We also collected conceptual outputs from Phase 2, final presentations from Phase 3, and observational notes. Thematic analysis was performed by eight researchers who independently coded the material, then discussed and synthesized the findings into four main themes.

RESULTS

Mockups

Following the workshop, eight initial IP concepts were generated, five of which were developed into complete design boards. These outcomes,

centered on the theme of “sports, fashion, and health,” illustrate applications of SMs across visible and tangible product areas, enabling personalized data interaction (Figure 5).

Functional analysis (Figure 6(a)) classified the designs into sports experience (3), office/home health (2), wearable devices (2), and entertainment (1). The predominance of sports-related concepts highlights participants’ focus on enhancing activity through realtime data perception. Designs also reflect growing attention to health in daily environments, indicating SMbased IP can address practical wellbeing needs.

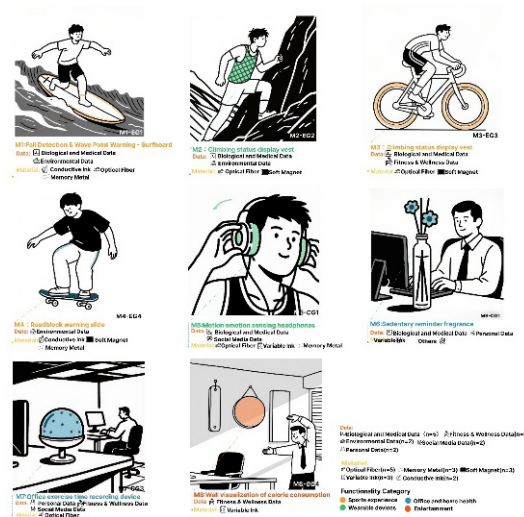


Figure 5: Visualization of 8 concepts from the workshop. M# - the index of each concept.

Data selection (Figure 6(b)) shows that all concepts incorporated dynamic data aligned with product attributes and user interaction goals, underscoring the role of context-relevant data in effective IP design.

SMs usage (Figure 6(c)) reveals shapechanging and light-emitting/color-changing materials as the most frequently employed. In sports equipment, SMs were integrated to enhance product functionality; in wearables, material comfort and optical properties were prioritized. These patterns suggest a preference for accessible, operable materials that support creative expression in IP.

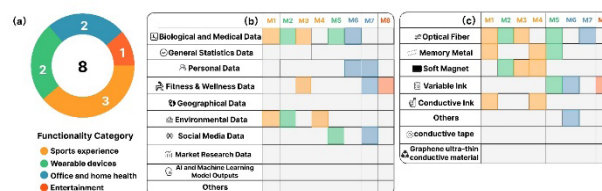


Figure 6: Classification of concept design outcomes by (a) functionality, (b) data classification, (c) smart material utilization.

Expert Evaluation

Five design experts evaluated the final concepts across seven criteria using a 5-point Likert scale. As shown in Figure 7, the experimental group (M1–M4) scored significantly higher than the control group (M5–M8) in Creativity, Interaction/Experience effects, and Material technology application, confirming that the APM-based Lumora framework and hands-on material cards effectively fostered creative and interaction-driven outcomes. While experts acknowledged the concepts’ creativity and experiential quality, they also noted concerns about practical implementation and industrial scalability, underscoring the need for further technical and design refinement to advance SM-based IP toward real-world productization.

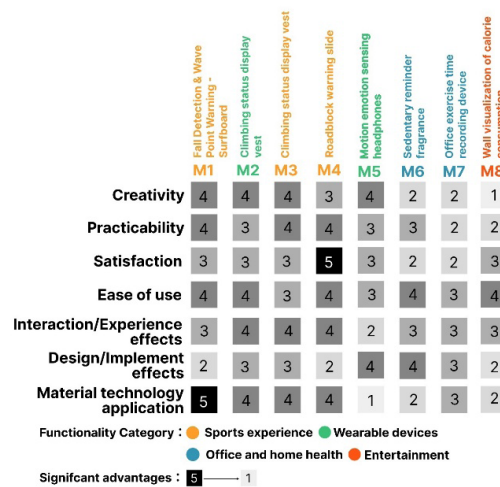


Figure 7: The rating results of the concepts from professional design team.

Quantitative Results

Framework Enhances Creativity and Self-Efficacy (H1)

CSI scores show that the experimental group rated creativity support significantly higher (M = 83.67) than the control group (M = 75.33) (Wilcoxon Z = 2.138, p < 0.05), with higher scores across all CSI factors (Figure 8). Self-efficacy (Cronbach’s α = 0.97) improved significantly in both groups after the workshop (experimental: Z = 4.826, p < 0.001; control: Z = 4.636, p < 0.001), with the experimental group showing greater improvement (Z = 4.825, p < 0.001).

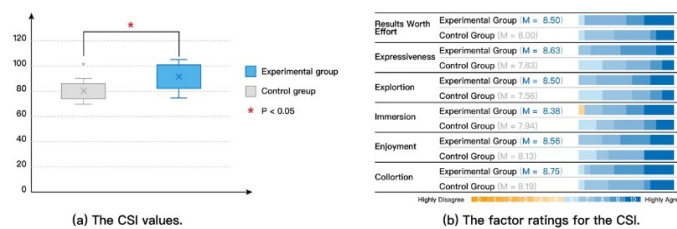


Figure 8: Results of CSI.

Table 1: Median (lower quartile, upper quartile), and Wilcoxon tests for self-efficacy.

Groups M (P25, P75)	Self-efficacy Questionnaire			
	Pre	Post	Z, p	Improv. *
Experimental Group	32.50 (29.11, 34.7)	91.33 (89.22, 92.64)	4.826 .000***	58.17 (54.81, 61.36)
Control Group	40.28 (35.4, 45.67)	58.39 (54.39, 60.53)	4.636 .000***	15.11 (13.25, 23.08)
Z, p				4.825 .000***

Hands-on SM Samples Improve Usability (H2)

The experimental group rated tool usability significantly higher ($M = 6.33$) than the control group ($M = 5.91$) ($Z = 2.087$, $p < 0.05$) (Figure 9). Perceived ease of use did not differ significantly between groups (experimental: $M = 6.33$; control: $M = 6.08$).

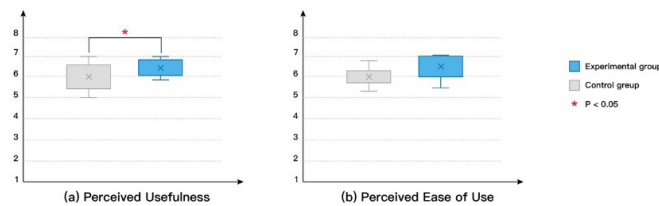


Figure 9: Results of the usability and ease of use scale. (a) perceived usability (b) perceived ease of use.

Summary

The results support H1, as APM-based tools significantly improved perceived creativity support and self-efficacy. They also support H2, as hands-on SM samples significantly enhanced perceived usability, though not ease of use.

Qualitative Results

APM Provides Comprehensive Guidance for IP Design

The APM-based card system supported structured yet flexible ideation, with participants reporting that the categorized design elements broadened their perspectives on sensory experience, data representation, and material selection. For instance, EP10 noted that *concepts like “balance” prompted deeper consideration of sensory duration*, while EP07 *valued the material taxonomy for enabling property-based choices*. The framework also improved design communication, allowing rapid grasp of material characteristics (EP2) and use of precise terminology (EP11), and helped translate inspiration into actionable plans while early identifying unfeasible elements (EP15) (see Figure 10 (a)). In contrast, control group participants cited knowledge gaps that

limited divergent thinking (CP22) and led to less coherent goals (CP27) (see Figure 10 (b)). Although the cards standardized process organization (EP3) and incremental development (EP6), users adapted them flexibly, often iterating non-linearly across categories to tailor the sequence to their group's needs.

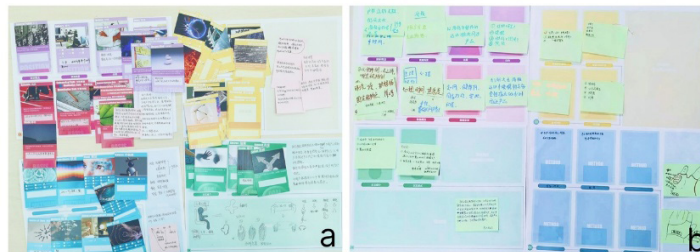


Figure 10: Tool usage. (a) experimental group. (b) control group.

Handson SM Integration Enhanced Novice Designers' SelfEfficacy

The integration of handson SM samples with cardbased tools enabled rapid design learning and sensorydriven exploration(see Figure 11). Direct interaction with materials such as thermochromic yarn provided tangible understanding of SM properties and supported concrete idea generation. Participants noted that material tactility and dynamic behaviors enriched data experiences and expanded design possibilities, while the framework encouraged the use of both primary and compensatory senses, for example, by augmenting motion data with visual or olfactory stimuli. This approach offered alternative design strategies and deepened attention to embodied, emotioncentered interaction.

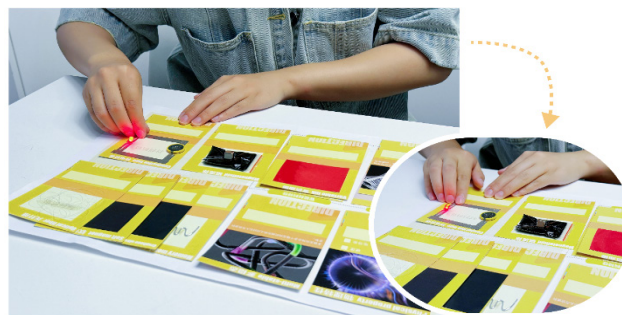


Figure 11: The overview of the MATERIAL cards.

Design Opportunities

Participants proposed material and format improvements, including magnetic attachments (CP22, EP11) for easy reuse and thicker cardstock (CP20) for durability. Card layout could be enhanced by printing secondary terms on the front for quicker reference, and a digital tool version was suggested to autogenerate design logic. To improve information accessibility, a concise

handbook with SM examples (EP15) was recommended to clarify technical terms like “anisotropy.” Further ideas included embedding QR codes for extended content (EP15) and enlarging card display areas for multicard viewing (EP16).

DISCUSSION

This paper presents an APM-derived framework and card-based workshop that integrates hands-on SM samples to guide novice designers in IP. We validated its effectiveness in enhancing creativity and usability (RQ1) and in supporting novices through tangible SM experience (RQ2).

Integrating Practical Knowledge for IP Guidance

The framework synthesizes interdisciplinary knowledge into a structured system that helps novices initiate and develop SM-informed IP designs. Participants reported that SM characteristics, material classifications, and case examples expanded their knowledge and aided material selection, reducing conceptual complexity. Unlike prior studies (Aarts et al., 2020) (Zhang et al., 2023), we observed users iteratively adjusting designs by moving between MATERIAL, DESIGN POSITION, and DATA cards, demonstrating flexible, nonlinear engagement. While crossdisciplinary frameworks are known to foster innovation (Sauvé et al., 2022), future work should continue bridging theory and practice (Halskov & Dalsgård, 2006) (Xue et al., 2024).

Hands-on Design Through SM-Embedded Cards

Existing card tools often represent theoretical structures (Wang et al., 2024) (Zhang et al., 2023); ours extend this by embedding physical SM samples. On MATERIAL cards, participants could interact directly with samples, such as attracting ferrofluid with magnets or lighting bulbs with conductive ink, gaining tangible understanding beyond text and images. Combined with provided DIY tools including clay and cardstock, this enabled rapid prototyping and realtime concept refinement. Feedback confirmed improved material comprehension and deeper engagement, aligning with prior findings on tangible cards’ role in sparking creativity and collaboration (Messerschmidt et al., 2022). Future designs could explore more modular SM integration (Liu et al., 2023) to enrich hands-on, sensory-driven exploration.

Practical Considerations for SM-Enabled Rapid Prototyping

Open-ended SM exploration effectively stimulated IP creativity. Embedding SM knowledge and samples as tangible TEI cards clarified design options and expanded the creative space. During the workshop, SMs were embedded in two ways: (1) in ideation, via sticky cards with physical samples and explanatory text; (2) in prototyping, through diverse SM materials that allowed realtime, tangible concept iteration. Participants noted strengthened material understanding and application. Future work may investigate more modular, scalable approaches to embedding SMs in design tools (Liu et al., 2023).

LIMITATIONS AND FUTURE WORK

This study is limited by the relatively narrow diversity of participants' design backgrounds, which may restrict the generalizability of the findings. Future work should expand recruitment and systematically categorize participants by their prior expertise in smart materials and interactive physicalization to better understand how background shapes design outcomes.

CONCLUSION

This paper introduces an APM-derived framework for IP design, materialized through card-based tools that integrate hands-on SM samples as tangible embedded interfaces. The Lumora framework, structured across five categories and 180 design elements, was evaluated in a controlled workshop with 32 novice designers. Results demonstrate that the framework and embedded SM samples effectively support novices in approaching IP design, enhancing creativity, confidence, perceived usefulness, and facilitating rapid knowledge application. This work offers a practical, sensory-driven approach to integrating smart materials into IP design and highlights the value of embodied experience in technology-mediated creative processes.

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