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UNDERSTANDING EMERGING MATERIALS AND THEIR INTEGRATION PATTERNS FOR DESIGNING NEW PRODUCTS WITH ENHANCED EXPERIENTIAL VALUE

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ABSTRACT
Material-driven design is a novel approach to product design, starting with a thorough understanding of the materials. The traditional design process determines materials at later stages. Materials have played a crucial role in research and practice, offering direction for applications aligned with the product's design and enhancing the product manufacturing process. Material research provides novel materials as superior substitutes for conventional ones and seeks the designers' collaboration to further their development. However, conventional applications have primarily used these materials. From an experience-value standpoint, the functional and experiential attributes of the materials may profoundly influence the overall design of a product. Nevertheless, design literature has not adequately addressed experiences with and for these materials, indicating that designers' objectives do not fully encompass their applications and integration in product design. This study aimed to first identify emerging materials that hold significant potential for product design. Secondly, it acquired a comprehensive understanding of these materials through a design ideation workshop with designers and subsequent interviews with material scientists. Third, we utilized the insights from these activities to conduct a concept design experiment with design participants. The aim was to explore the integration of these materials and the experiences they may elicit in product design concepts. The results provided valuable insights into understanding emerging materials and their integration patterns in new product designs, enhancing the product's experiential value and functional aspects in an envisioned scenario.

Keywords: Material integration, experiential value, material understanding, emerging materials, concept design

1 INTRODUCTION

Generally, the design process begins with a problem-driven or need-driven approach for a product design and considers material selection in the detail design stage [1]. Designers consider the technical characteristics of a material in a product to support its application, but they often overlook the experiences that a material may evoke [2]. Material-driven design (MDD) is a novel approach that begins with a thorough understanding of materials, both technically and experientially. It then identifies the optimal situational whole in which the material is most suitable for a product. This approach has enabled designers to leverage the experiential attributes of materials and identify integration possibilities with other materials [3]. This approach can enhance the significance and worth of materials, surpassing those with a single use and limited potential for innovative exploration. Design researchers recommend leveraging the properties of new materials to stimulate innovation and create new opportunities for artistic interaction within products and environments [4]. The use of novel or unused materials can produce innovative product forms and aesthetic experiences, underscoring the need for developing materials or manufacturing processes to actualize product concepts [5]. Consequently, it is imperative for designers to understand the characteristics of materials, their sourcing methods, processing methods, and types, as they are essential to the design process. Design practitioners have demonstrated the feasibility of implementing various aspects of material experience, whether in a general context or a more specific context on aesthetic and functional aspects. Some of these experiences are the expressive sensorial atlas [6], the multi-dimensional materials charts [7], the meaning-driven materials selection [8], the color atlas [9], design with Wabi-Sabi [10], the textile atlas [11], the aesthetics of tactual experience [12], and materials and emotion [13]. Moreover, Howes et al. [14] discovered the effects of material sounds and tastes on users' experiences of products. Chapman [15] investigated the emotional connections with materials in relation to durability and long-lasting experiences. Despite previous attempts to understand existing materials for their aesthetic, functional, and experiential features [16, 2-4], there is still a gap in understanding and integrating new emerging materials with their multiple experiential features. Adding to this, several design researchers argue that in practice, designers often lack proper familiarity with the potential applications of materials and their experiential characterization [17, 18, 4]. This study aimed to identify key emerging materials, explore their potential aesthetic and functional features, and understand material integration patterns. The purpose of the integration patterns is to propose new design concepts with experiential value, which encompass aesthetic (sensorial), interpretive, affective, and performative experiences within a situational whole, based on envisioned scenarios. We conducted several visits to two local science and technology institutes to observe and understand potential materials with novel characteristics that can have multiple applications in product design. Our preliminary observations and engagements with material researchers enabled us to identify key emerging materials with particular applicability in their domains. However, we could not use these materials in the design, even for experiment purposes. Despite the potential benefits, the materials' applications remain challenging due to the lack of a fully developed sample for technical and experiential characterization and the absence of a formal process for transforming a product concept into reality. As Rognoli [6] argued, designers are the ones who define the expressive and affective aspects of a product experience. In the absence of actual material samples, designers may conceptualize the experience utilizing alternative materials that possess similar sensorial qualities and physical properties [3]. We conducted an ideation workshop with designers to analyze the possibilities of the materials used in the design process, assess their limitations, and explore their potential applications in the product design [4]. Subsequently, we conducted interviews with material researchers to further reinforce the findings from the workshop. We used our existing understanding of the materials to conduct a concept design experiment with 10 postgraduate design students, with the aim to identify material integration patterns and their connection to specific experiential aspects, emphasizing that functionality is a prerequisite for a proposed product design concept. Furthermore, the experiment aimed to validate our design activities by identifying key emerging materials, understanding them based on limited available knowledge, and devising meaningful integrations into product design concepts that evoke valuable experiences. This study presents potential research directions for designers focusing on material-based design thinking. The study aims to gain new insights into the effectiveness of material-driven design methods for diverse product design expeditions, resulting in innovative product design experiences. Furthermore, this study provides valuable insights for material researchers, aiding in the advancement of materials in development. This, in turn, enhances their utility, value, and versatility in product design, thereby eliciting enhanced experiential characteristics and ensuring their effectiveness and worth in intended applications.

2 RESEARCH APPROACH

Before commencing the main study, we first visited numerous materials science labs to discover emerging materials for multiple design applications. These materials include thermoelectric generating (TE) paint, printed batteries, electric energy-storing paint, 3D printable microorganisms, and 3D photochromic soft photonic crystals. Material researchers wanted to find further uses for these materials. Therefore, we investigated these materials' intended uses to better understand their characteristics and applicability in product design. The researchers developed TE paint for furnaces, industrial boilers, and other heat-loss equipment. Current thermoelectric generators turn heat into electricity. These generators are flat 3D modules; thus, only a tiny section touches a circular furnace surface, wasting thermal energy. In contrast, TE paint clings to any surface like conventional paint, minimizing gaps and converting heat energy into electricity. This allows us to analyze the usability of TE paint, identify new applications for its unique qualities, and engage in design discussions. It is useful and attractive to paint since it generates power via heat and works on numerous surfaces. After successful visits to materials science labs, we reviewed literature to identify new materials with multiple aesthetic and functional properties for product design. We added these new materials to our list and learned more about their aesthetic and functional properties.

Second, we conducted a design ideation workshop where we provided a list of key emerging materials to the design participants without using the MDD method—a method to understand and design for material experiences in product design [3]. In particular, the workshop aimed to understand the obstacles that hinder product design processes, preventing designers from leveraging emerging materials with multiple properties that contribute to the aesthetic (sensorial), interpretive, affective, and performative experiences of a product. We found that designers lack knowledge about potential applications of emerging materials for product design; their creativity is limited due to their inability to deviate from established product design solutions. Moreover, the current product design scope limits their ability to explore beyond traditional product design processes. Therefore, we delved into the constraints of understanding these materials during the design process while also identifying envisioning potential applications of the key emerging materials in future product designs.
Third, we conducted interviews with material researchers to gain insights into emerging materials and to learn about the design possibilities and future uses of these materials. Having listened to both design participants and material experts, we articulated the potential integration of specific materials to create unique experiences in product design.
Finally, we conducted a concept design experiment, drawing inspiration from the previously mentioned activities. The aim was to incorporate new materials into product design and allow participants to leverage emerging materials to design products with improved aesthetic and functional experiences. We incorporated the MDD method into the experiment to introduce the participants to a specific material-based design process. This can allow them to understand the materials through their experiential features and produce new design concepts.

2.1 Design participants

We recruited 10 design participants, including seven females and three males, with ages ranging from 25 to 30 years, for the concept design experiment. They were postgraduate students majoring in product and industrial design at a local design institute. Participants had more than two years of prior experience in product design and had the ability to handle complex design tasks. This study received approval from the institutional review board (IRB) of our institute with reference number HSEARS20221103006. Figure 1 shows participants design activities and the design environment.

Figure 1. A participant design activity and the design environment

2.2 Design tasks

In order to educate the design participants about emerging materials, we gave them a catalog based on the results of the ideation workshop and interviews. We then asked the participants to utilize the unique technical and experiential characteristics of the materials in the catalog. Additionally, we asked them to design new product concepts, enhance existing products, or create a system that combines both functional and experiential components. We introduced the participants to the MDD method for experiential characterization on four distinct levels, which is an essential component of designing for experiences. This introductory part also served as a task to understand the process, which employs a conversational strategy to accommodate uncertainties [19]. We also conducted a brief exercise to familiarize the participants with the main task, which involved assigning experiences to individual materials and their contribution to the overall experiences of a product in a situational context. After ensuring their understanding, we handed over the design brief, and a material catalog, which included information about the technical and experiential characteristics of all identified materials. Before proceeding, participants had the opportunity to ask questions about the task. The design brief stated that the main task was to either design a concept for a product or system or devise a solution to improve the aesthetic features or functional experience of an existing product using the materials available in the catalog.

2.3 Experiment setup and measures

We conducted the experiments in a meeting room free from external distractions. We provided each participant with all the conventional tools necessary for sketching their design concepts, including a sketch pad, pencils, sharpener, eraser, ruler, and sticky notes. We allowed them to use the provided tools to express their concepts. The invigilator observed the participants' design activities, took notes continuously, and informed them that the process would take two hours. There were no restrictions during the concept design process. After the design activities, participants were required to fill out a self-reflective form while verbalizing the reason for certain responses and explaining their design concepts. Subsequently, based on the notes taken during the concept design process and the self-reflective form, we conducted a retrospective interview to gain further insights into the decision-making process and envision the experiential and functional aspects that constitute the participants final concepts.

2.4 Data collection and analysis

The participants filled out a self-reflective form and explained their design concepts and how they envisioned them for the intended user at four distinct levels of experience. We conducted retrospective interviews based on the insights gained from idea generation with inspiration, the application of emerging materials, the intended user's experiential evaluation, and the usefulness and novelty of the application. We quantitatively analyzed all the data from the self-reflective form to identify only those product concepts that demonstrate a sufficient understanding of how materials and products function in the envisioned scenarios. We achieved this by counting the number of experiences that each participant wrote down on their paper. An increased number of experience counts indicates that the participant had a deep understanding of the experiential aspect of the materials. Additionally, the product they proposed had a high experiential value, indicating more thought put into the concept. Conversely, those with fewer experience counts suggest that the participant either had a poor understanding of the experiential aspect of the materials and product or, even if they had a good understanding, their proposed concept product had a low experiential value, leading to the exclusion of their concepts. We examined the verbal protocol data recorded during the concept design experiment. For each successful concept, we asked the participant to describe the envisioned scenario and the experiences they thought the product would provide for the intended users on four levels: aesthetic (sensorial), interpretive, affective, and performative [2]. In order to extract valuable insights based on material understanding, we transcribed the interview data for qualitative analysis. We then generated a coding scheme and categorized the transcribed data into themes and subthemes. The following elements formed the foundation of the coding scheme:

- Basic decision-making process–the process of basic decision-making involves inspiration, integration consideration, product selection, and anticipating the expected outcome.
- Product experience–how will the user experience the product in the proposed environment and over time?
- Evaluation based on functional and experiential novelty–how they perceive their product as a valuable addition and a novel use of emerging materials.

3 RESULTS

3.1 Overall concept designs

The design participants envisioned products in an experiential manner based on the materials. The concept design experiment directly links the understanding of experiences elicited by the product with the understanding of material, which in turn relies on the identification of emerging materials. Based on the total experience counts provided by each participant in the self-reflective forms, we analyzed a total of 10 concept designs and only concepts with experience counts higher than the average across all levels of experiential value were considered for further study. Among them, the VR gaming suit, companion seat, health monitoring vest for the elderly, and stuff toy were selected for further study.

3.2 Selected concept designs

3.2.1 VR Gamming suit

The VR gaming suit is a concept that utilizes wearables on body joints to record muscle movement and replicate it in a virtual world environment. Body heat self-powers these sensors, requiring only raw stimuli signals to reach the main device. The headset has a 3D electrochromic soft photonic crystal display, ranging from transparency to full color, allowing users to interact with people in the immediate environment without taking off the headset. This allows for AR and VR in the same system, unlike other headsets like HoloLens, which only works for AR/XR applications. While other headsets such as Oculus, Meta Quest, and Apple Vision Pro can create fully virtual environments, they only offer pseudo-real XR in their later versions. The dynamic chromic property of 3D electrochromic soft photonic crystals enables the creation of a fully opaque VR environment and XR, which can be augmented with the real environment, thereby enhancing natural and direct interaction. Movement-based interaction is more natural with wearables than handheld remotes, and AI models can detect hand movements for certain controls. The concept also proposes a more artistic approach to processing, using a flexible R2R printed circuit that extends along the neck.

In sensorial experience, the material of this gaming suit will be flexible and soft for comfort, and it will be visible with the lights inside the glasses. It can also be transparent in ambient mode for interaction with the surrounding environment. The interpretive experience will completely transform the in-game interaction, making it a futuristic product. Its valuable materials will undoubtedly enable these advancements over traditional VR sets. The affective experience should instantly evoke a sense of coolness due to the headset's transparency feature, the ability to turn back to a fully colored screen to return to the virtual environment in a game or other VR experience, and the natural movement sensed by the other parts and replicated accordingly in the virtual game world. In the performative experience, the new layout will draw attention and stimulate game exploration. This could potentially motivate them to spread the word to their friends. They may ask about the sensing components' materials and the headset's creative circuitry. Curiosity may lead consumers to try competing items to duplicate this amazing experience.

3.2.2 Companion Seat

The companion seat concept is a flexible and transformable seating option that combines a friend-like object with various seating options. It is designed with a flexible composition layer that incorporates segments of electrochromic, photochromic, electromorphic, and photonic crystals. This layer reacts to electric, light, and pressure signals, changing color and texture accordingly. This creates a multisensory interaction between the user and the product and the environment around it. The product's colors are indeterminate and live-like, setting it apart from other products with built-in reactions controlled by computational models. Its reactivity to light results in chromic and morphic properties throughout the surface. Even if the user is not around or using the product, it remains receptive and reactive to its immediate environment. The transition from one color to another is non-binary, taking its natural time depending on the intensity of the lighting environment. These features make the user think about the environment for the companion seat even after leaving the space, potentially finding it in a different form depending on any odd changes in the environment.

In sensorial experience, people will perceive it as a soft, flexible round bag, similar to a beanbag, with color-changing properties. It will be sensitive to the lighting environment due to its photochromic/morphic materials, which will change color and texture based on the lighting conditions. Its size will be large enough to accommodate a person. In interpretive experience, it would be a very comfortable place to sit on, very friendly, expressive in a colorful way, and a warm, cozy, and soft thing to have around. In affective experience, it can react to its immediate environment without a human user, so it may not be in the same color and texture as before, which will interest the user in the material/surface and the memory foam will provide comfort. In performative experience, the memory foam and flexibility of the form allow the product to be perceived in various shapes, allowing the user to sit on it, use it as a supporting rest, or even stand or lean on it if we build a specific fixture with it to aid in standing. This allows for a welcoming exploration of different forms.

3.2.3 Health Monitoring Vest

A health monitoring vest is a wearable piece of clothing with flexible pressure sensors and a layer of TE paint for temperature sensing. It is connected to a server that connects it to potential stakeholders, such as caretakers of the elderly, who can stay informed about their health. This vest can empower the elderly and allow them to perform their jobs without worrying about their health. The vest's scalability makes it ideal for health monitoring in hospitals, eliminating the need for frequent visits by doctors. It can also be integrated with an AI model to provide doctors with information about a patient's recovery progress and identify emergency situations. This device is more suitable for wards where EMG electrodes are not suitable or needed, as it does not restrict normal movement. The vest is compared to a smartwatch, which is limited to the wrist and monitors confined variables. Conventional clothing like this vest can have a greater impact on health monitoring than specialized equipment, which may impose restrictions and create a sense of constant monitoring. However, the participant expressed uncertainty about the manageability of implementing conventional clothing, its durability, and the importance of considering comfort when wearing it.

In sensorial experience, from a sensory perspective, this vest should be soft, similar to any other fabric-based wearable. It should also fit snugly to enable the embedded sensors to detect bodily movement, feel warm to the touch, and potentially be blue or green in color if it is intended for hospital use. In interpretive experience, since it is a simple piece of clothing, the elderly should perceive it as something new, unique, and high-tech. Therefore, it should be lightweight and comfortable to wear at all times. In affective experience, for the elderly, receiving care from their son/daughter will be a delightful experience, while for the caretakers, being able to stay connected while away and ensure their elders' safety will bring a sense of relief. It may seem strange that a simple piece of clothing can monitor these things, but it will also serve a very functional purpose. In performative experience, in the long run, this will facilitate an active lifestyle for both the elders and the caretaker, as they will feel more connected to each other and find it easier to go out and away at times. The elders will feel special when they wear fancy, light, and unique clothing, which can empower them to spend time with themselves without worry.

3.2.4 Stuff toy

The product concept is a lifelike toy with 3D electrochromic soft photonic crystals that display different colors based on the pressure applied when hugged. This chromic property is powered by a printed battery that stores the charge from TE Paint generated by body heat/warmth. When the user hugs the toy, it converts the heat energy from the human body into electric energy, which powers the pressure-sensitive chromic property of the 3D soft photonic crystals. This concept resonates with the concept of emotional energy transfer when two loved ones hug each other. Hugging the toy increases its expressiveness by responding in the form of colors. However, it will not show any colors or be very colorful, indicating an emotional gap. Regular hugging is necessary to keep the toy energetic. This product represents a significant departure from conventional stuff toys that lack responsiveness to emotional acts. While some toys incorporate embedded music and lights, they typically respond in a binary or overly controlled manner, making them neither truly alive nor evoking a deeper sense of emotional attachment.

In sensorial experience, stuff toys need to have the sensory experience at the highest level for people to assume they have them, so this one will be cute-looking, smooth, and soft-surfaced, so it will be visually very appealing. In interpretive experience, it will be a cute thing to have; cute is a singular word that can collectively represent the blend of friendly, cozy, comfortable, and a factor of warmth in aesthetics and experience. In affective experience, the small (not tiny) form factor will make it easy to carry and keep close, the soft and rounded material will make the user feel comfortable, and hugging the stuff toy will relieve stress and show colors in the hug while charging the battery with body heat. Therefore, the process empowers both the user and the object, making it feel alive. In performative experience, the affective experience suggests that hugging and keeping the toy around can create an addictive sense of belonging and friendliness, leading people to keep it around and even bring it to bed. This practice not only keeps the toy alive but also alleviates stress for the user.

3.3 Results of thematic analysis

3.3.1 Inspiration for the product

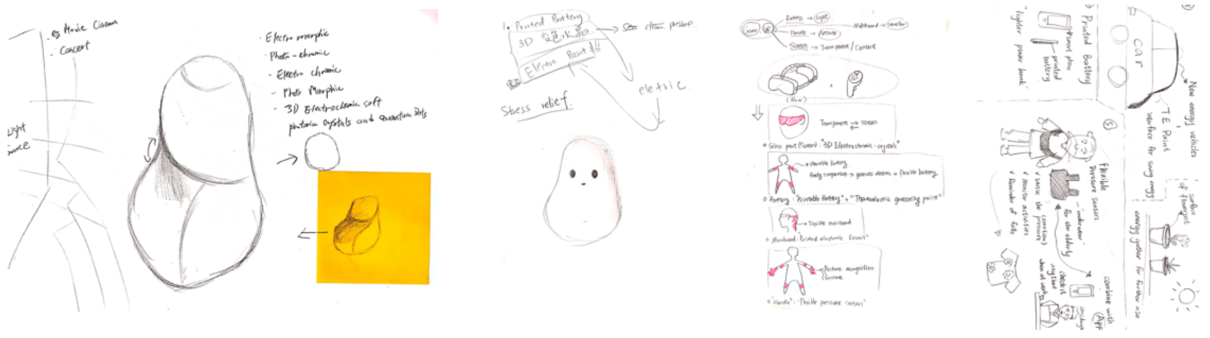
Two basic patterns were observed for inspiration: firstly, the process starts with a personal fascination, aiming to incorporate various materials into the objects of interest. Secondly, the focus shifts to the materials themselves, with the aim of identifying more effective applications. Three of the four successful concepts began with materials, and their unique properties triggered objects of personal interest or products they had previously experienced. However, only one concept—stuff toys—started from their personal interest in stuff toys, focusing on the materials' flexibility of application, which resonated with the toys' flexible behavior. At some level, this was also triggered by the unique property of the materials: flexibility of application. Later, the participant attempted to integrate the in-depth properties of the materials to enhance the object experience at different levels.

3.3.2 Envisioning experiential depth

It is fascinating to observe the patterns that emerge from this theme of envisioning the end user with the product. Two basic themes stand out here: Firstly, they serve as inspired or improved versions of existing products, and second, aspirational or innovative new products. All the successful product choices were derived from direct experience with similar products, such as VR gaming suits, stuff toys, and companion seats, or from their role as primary stakeholders in a specific problem, such as the health monitoring vest; even the later product was based on conventional clothing. They were able to better envision the end user's experience with the product due to the accessibility of the product's merits and demerits, which enabled them to understand current user sentiment and identify potential enhancements to improve the experience. They themselves had been the primary users of those existing products, so they were primary stakeholders in the former process to assess the experience in depth. Interestingly, all other product concepts that could not score experientially high enough as described by the participants were much more novel/new/innovative in nature, like bamboo rollable computers and cooking assistants, so it must have been hard to envision a user for products that did not exist before in a version close to the envisioned one.

3.3.3 Patterns of integration

Participants were free to integrate the materials in any way that best fit their concept. The integration patterns included incorporating these materials into IOT products, such as those connected to mobile applications or another server, general-purpose products like cooking aids, and entertainment items like toys. Here, two themes were emerged: the first was integration, supported by a computational model, and the second was integration within and as an analog medium. The first concept pertains to the integration of emerging materials, where a computational model either processes or stores data or responds instantly to external stimuli. The latter concept refers to a more natural integration of materials, known as analogue, where the material experience relies on its inherent behavior in response to specific external stimuli, independent of any computational model's control. It is worth mentioning that half of the concepts were based on a computational model: the VR gaming suit and the health monitoring vest. The materials acting as sensors would collect data, which would then be processed by the computational model, whereas the other two—the companion seat and the stuff toy—had the materials integrated to behave in their natural orientation. Interestingly, the later ones reported that their concepts exhibited behaviors akin to those of living things. The participants concept design sketches are presented in Figure 2 as an example.



Companion seat Stuff toy VR gaming suit Health monitoring vest

Figure 2. Participants' design sketches

4 CONCLUSIONS

This study aimed to apply the knowledge design participants gained about key emerging materials to develop potential product design concepts that leverage these materials' unique qualities to enhance the overall product experience. Previously, there was no definitive study demonstrating the feasibility of understanding and integrating materials for product design concepts. Engineering designers often synthesize materials based on proposed uses. This research established a foundation for designers to explore materials and integrate them into product designs. It can enhance product experiences and enable material makers to develop materials with a wider range of functional and experiential applications beyond mere specific functions. We initially evaluated the concept designs using a quantitative assessment of the participants' understanding of the process, focusing on the experiential value of their design concepts. We then conducted a qualitative analysis of the design concepts, focusing on those who had a thorough understanding of the process and material experiences. We focused on the themes of integrating emerging materials into new or existing products and exploring the types of experiences these materials bring to the final product design concepts. We discovered an intriguing method of utilizing materials as analog mediums to generate experiences based on their inherent behaviors rather than relying on a computational model for control. Despite the novelty and aspirational nature of the design concepts produced by design participants, there was a noticeable lack of confidence in them. Furthermore, we discovered themes of interactive experiences that evoked a sense of life, stemming from specific personal encounters and relying on the fusion of various materials to create a product that embodies life within a given context. These characteristics align with those previously discussed by Hobye and Ranten [20], Barati et al. [21], and Petreca et al. [22]. However, while these studies based their personal assumptions on the term "alive" for the product and processes, this study also provided empirical evidence for the existence of live experiences. We found a significant subjective difference in the way participants reported their work, based on their personal understanding of the levels of experiences. Some participants reported deeper experiences than others, which could potentially yield more value. Therefore, a more thorough and equitable evaluation is necessary to guide the future extension of this practice in a meaningful direction. Our future research will first expand this sample to gather more robust evidence about the designerly way of integrating these materials. Additionally, our aim is to gather actual material samples to explore the potential of integrating these materials as analog mediums to create naturally occurring experiences. Finally, our intention is to explore the integration of these materials with other materials to create a situational whole that interacts and exists in a lifelike manner. Subsequently, we aim to obtain expert evaluation and user testing of functional prototypes, as recommended by researchers for such aspirational product integrations. The current study has elucidated the process of understanding emerging materials to develop their integration patterns for product design concepts, taking into account the experience visions these materials convey, which can be incorporated into a final product in a variety of scenarios. We showcased our design activities, which aim to enhance the understanding of materials by integrating their technical properties and experiential qualities with the intended users' perceptions. These activities indicate that when materials exhibit diverse experiential characteristics and their integration becomes a crucial aspect of the design process, the designer must first understand the material's attributes and explore its experiencing dimensions. Subsequently, they must integrate these elements to create a vision of the material's experience, which they can then transform into a tangible product that aligns with various envisioned scenarios.

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