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Understanding Experiential Qualities of Light-Touch-Matters: Towards a Tool Kit

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Abstract

The present paper is about the tools and strategies, designers adopt and develop to support their understanding of an underdeveloped smart material composite. Referred to as Light-Touch-Matters or in short, the LTM materials, the composition is proposed by materials scientists, integrating the two smart materials of flexible thin-film Organic Light-Emitting Diodes and piezo-electric polymers. In a project funded by European-Union, materials scientists and designers joined forces to further develop such smart material composites through early design input. In order to introduce and represent the LTM materials to designer's prior their actual development, materials scientists mainly used abstract descriptions, 'key' physical properties and sensing/actuating function. Such representations, however, hardly capture the experiential qualities of LTM materials, which concern how they gratify our senses and what meanings, emotions and actions they elicit. This paper has conducted four design case studies to identify the design approaches and representational tools used and developed by designers for understanding, exploration and communication of the experiential qualities of these underdeveloped smart materials. Discussing the limitations of the identified tools in terms of capturing the dynamic and performative qualities, the paper draws further implications towards a future design Tool Kit.

Keyword

Smart Materials, Materials Experience, External Representations, Design Tools, Design Process

Introduction

Light-Touch-Matters (LTM) is a project funded by European-Union (2013-2016) with a prospect to innovate smart materials' development through design influence. The project is unique from many respects including;

1. Proposing an alternative material development scheme by involving product design in co-development of a new smart material composite

2. Subjecting both material developers and designers to reflect on the purpose of the material prior and, in parallel, to do some rigorous material experimentation

The proposed smart material composite in the LTM project, the LTM materials — the plural form considers the possibility of more than one composition— is composed of two smart materials, namely thin-film Organic Light-Emitting Diode (OLED) and piezo-electric polymer. The underdeveloped state of the LTM materials, referring to the underspecified properties and experiential qualities of the eventual composites, creates a unique opportunity for designers to influence the materials' development, possibly a *design-driven* material development (cf. Verganti, 2009). However, designers' understanding of these underdeveloped smart material composites is likely to be hampered by early material development conditions, such as having no or few laboratory samples, limited product-related design knowledge and application precedents of the composites. To mobilize the application design process, the materials scientists represent the LTM materials through descriptions of their *key* physical properties and sensing/actuating functions, as well as a schematic representation of their structure (Figure 1).

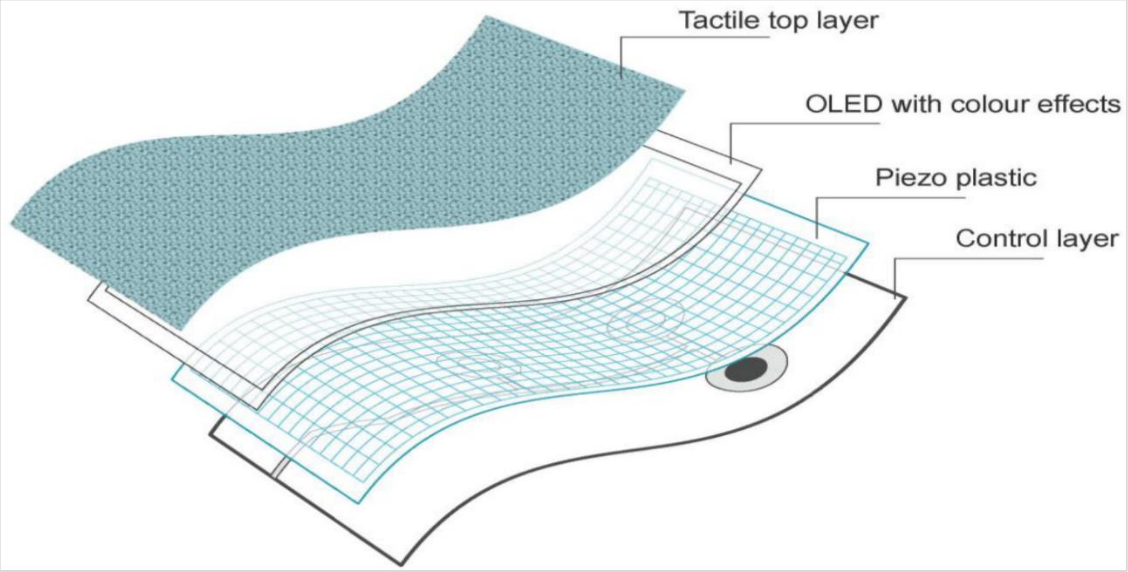

Figure 1: *The schematic representation of LTM materials (Source: Miodownik & Tempelman, 2014)*

Over the past decade, design researchers have extensively discussed the limitations of scientific concepts, material databases and selection tools, when communicating the sensorial and product-related material information, required by the designers (e.g. Karana et al, 2008; van Kesteren, 2008). It is evident that in design practice, material samples and product parts are commonly used to compensate for the limitations of technical information (Kesteren, 2008). Using material samples to complement the technical datasheets provided by suppliers, may resolve the needs of the design projects dealing with fully developed materials. But what can be done in situations where the material is unknown, complex and underdeveloped? The Pioneering research initiatives, such as the LTM project, are particularly valuable to bring the design influence in the early stages of material development (Bergström, 2010; Miodownik, 2007). Given this imperative, our research program focuses on finding ways to support designers in a better understanding of underdeveloped smart material composites and their experiential qualities.

The possible roles of designers in co-development of new materials may include the exploration and communication of a new material’s potentials and demonstrating their applications (Nathan et al., 2012). The *potentials* of a material in design, as highlighted by Manzini (1989) as well as other scholars in the field (e.g. Karana, 2009; Bergström, 2010), refer to the possibilities in relation to both utility and experience. Unlike a rather abstract account of functional possibilities in relation to certain material performances (e.g. high abrasion resistance), experiential possibilities are unfolded in direct interaction with materials and might not be easily captured from technical properties and schematic representations. Recognition of *experiential qualities* of materials, i.e., qualities that materials elicit in human-material interaction (Karana et al., 2008; Karana et al., 2014) on top of their functional role within the process of product embodiment, has led to theoretical frameworks (e.g. Wiberg, 2014; Giaccardi & Karana, 2015) and design tools (e.g. Van Kesteren, 2008; Karana, 2009; Zuo, 2010; Rognoli, 2010). These tools and theories provide methodological and analytical support towards a broader understanding of materials as well as a cross-fertilization of the possibilities.

Geared up to smart materials, researchers have emphasized a need for understanding their dynamic properties and possible experiences that emerge in time i.e., temporal form (Vallgårda & Sokoler, 2010), in *continuous negotiation* with context and in use (Bergström et al., 2010). Dynamic qualities of smart materials and technical complexities, involved in exposing their experiential qualities, set out new challenges for design (Vallgårda & Redstörm, 2007; Bergström at al., 2010). One of the most discussed challenges is that smart materials require embedded interactive systems to reveal their dynamic qualities (e.g. Addington & Schodek, 2005), meaning that static material samples would not be enough for representing their qualities. Combinations of linguistic approach and prototyping are suggested to capture the possibilities that emerge in direct interactions with these materials (Bergström et al., 2010). Even though these approaches may support understanding of experiential possibilities through design representations, discrepancies between the media of representation (e.g. electronic hardware) and the actual smart materials are inevitable (Bergström et al., 2010).

In order to understand the challenges of understanding and designing with LTM materials, we take a designer-centered approach. The research questions motivating the present study in the first place are: *How do designers understand LTM materials and their potentials? What tools and strategies do designers use in understanding, exploring and communicating the experiential qualities of these underdeveloped smart material composites?*

Our theoretical understanding of the material’s experiential qualities is based on Materials Experience framework, proposed by Giaccardi and Karana (2015). The following section will explain this theoretical lens followed by other related works, concerned with materials understanding in design. Next, the role of material/design representations is explained in relation to understanding, exploration and communication of the experiential qualities. With this background, the research method (i.e., the case study) is presented. Four main approaches towards exploring the potentials of the LTM materials are identified after analyzing the design activities in and across four design process cases. Furthermore, the study identifies the probes and representations, used to understand, explore and communicate the experiential qualities of the LTM materials, discussing them in three categories. Reflecting on these findings highlights the need for high-fidelity, multi-modal representations of the LTM materials early in the process in order to draw further implications to words a future design Tool Kit.

Materials’ Experience: An Analytical Lens

Initially a notion introduced by Karana et al. (2008) and later elaborated by Giaccardi and Karana (2015), materials’ experience is concerned with how materials are experienced, in terms of qualities and performances they constrain, among other factors constituting an experience. Giaccardi and Karana (2015) provided a theoretical lens to decode the *patterns of experience with materials*, through four *experiential* levels: *Sensorial*, *Interpretive*, *Affective* and *Performative*.

According to their proposed framework, materials with their inherent properties affect our five senses at the sensorial level, elicit meanings from us at the interpretive level, evoke emotions at the affective level and trigger actions at the performative level. For instance, the specific fake-fur material of a jacket may look *cheap* — interpretive level— or *surprisingly soft and velvety* — affective and sensorial levels— or may smell *synthetic* — sensorial and interpretive levels— or may make you *gently rub it against your skin* — performative level—. In reality, such diverse elements, constituting our materials' experience, are intricately interconnected and do not unfold in any specific order. By exploring how people experience the materials of things in-situ and over time at these four levels, the *experiential qualities* are better understood (Karana et al., 2015).

An in-situ and/or longitudinal investigation of the experiences of new and underdeveloped materials might not be possible as they are not yet being used in product applications and/or situated in use contexts. Karana et al. (2015; 2018) claimed that in design processes that depart from such materials, an understanding of the material's experiential qualities can be obtained through the users' study of the existing material samples along with comparisons of their results. The observations and investigations of how people interact with material samples can inform the designers about the possible role of material properties to encourage and prevent certain patterns of materials experience. These may include descriptions and analogies, used to describe materials, non-verbal expressions and actions observed in material-people interactions. In addition to research methodologies that support an understanding of the experiential qualities, designers need to inquire about and anticipate *how certain experiential qualities might be changed or preserved* in future compositions. In other words, they need to develop a sense of dynamic relations between the experiential qualities and other design variables such as material's physical and dynamic properties, product form and function and the context of use. The role of design representations and prototyping has been persistently emphasized when supporting the design team's understanding, exploration and communication of the experiential qualities of products, prior to their existence (e.g., Buchenau & Suri, 2000; Bergström et al., 2010). In the following sections, an overview of the existing literature on materials understanding and external representations in design shall be provided. Such background seems to be necessary for employing the framework of *Materials Experience* as an analytical lens during the design time.

Materials Understanding in Design

As some indispensable sources for inspiration and information, physical materials (e.g. material samples, product parts, etc.) are frequently used in different stages of design (van Kesteren, 2008). The importance of seeing and feeling materials in design, inability of scientific concepts and numbers in capturing and communicating such experiential knowledge have been discussed extensively (e.g. Ashby & Johnson, 2009; Karana et al., 2008). Due to the incompatibility of human experience and scientific concepts, researchers have suggested alternative ways of communicating the experiential qualities mainly through language (e.g. *Modes of appearance* in study of color, Katz, 1935; Manzini, 1989). In the fields of design and architecture, understanding and demystifying the relations between material properties and experiential qualities has been a focal interest (e.g. Karana, 2009; Rognoli, 2010; Zuo, 2010; Wastiels et al., 2012; Wilkes et al., 2016). On a practical account, these works suggest how to gather information about experiential qualities and conduct user studies, offering useful design tools such as Meaning-Driven Materials Selection (Karana, 2009), Expressive-Sensorial Atlas (Rognoli, 2010) and Material Aesthetic Database (Zuo, 2010). The proposed tools are primarily considered to support material selection activities in design and design education.

Understanding of materials in design has gone through transformation in response to at least two developments over the past ten to fifteen years. The first one is an increasing interest in material-driven design, referring to the design processes that depart from specific materials. Instead of thinking about the possibilities of new and emerging material, designers take interest in tinkering with those materials, making new samples and exploring the experiential qualities the samples elicit in people (Karana et al., 2015). One striking feature of material-driven design projects is a distributed materials understanding across design phases, which contradicts the common prioritization of form over materials in modern design culture (Oxman, 2010). In design cases presented by Manenti (2011), Bohnenberger (2013), Jordana et al. (2015) and Karana et al. (2015), to give only a few examples, the materials are processed and experimented early on during the design process to inform possible forms and qualities of the eventual application.

The second development is the *material-turn* in interaction design (Wiberg & Robel, 2010) and an increased interest in materials and their possibilities for novel user interfaces and computational composites (e.g. Vällgarda & Redstörm, 2007; Döring et al., 2012; Wiberg, 2016). The materials-turn in interaction design has motivated theoretical frameworks to support understandings of materials in relation to the qualities intended in design along with the ones, elicited *in use* (Jung & Storlterman, 2012; Giaccardi & Karana, 2015). What greatly distinguishes material-centered works in interaction design from any traditional account of materials in the design is the account of temporal form (Vallgärda & Sokoler, 2010) and dynamic context-dependent qualities of materials compositions (Bergström et al, 2010). The works of Coelho (2007) and Franinović and Franzke (2015), for instance, invest in manipulating smart materials directly through hands-on experimentation, to realize their *transient* and *transformational* qualities (Brownell, 2010).

The abovementioned literature suggests that for composite materials (e.g. Karana et al., 2015), smart materials (e.g. Coelho, 2007; Franinović & Franzke, 2015) and digital technologies (Sunderstörm et al., 2011), an early understanding of the material/technology properties and constraints can open up new design possibilities. However, in case of underdeveloped smart materials, the understanding of technical properties and experiential qualities cannot be obtained through direct experiences and experimentation with actual material samples. The question is therefore, how the — potential— experiential qualities might be investigated? The works of Vallgårda and Redstörm (2007) and Bergström et al., (2010) provided an alternative: to experiment with substituting materials and develop low-fidelity compositions of digital technologies and physical materials, i.e., computational composites (Vallgårda & Redstörm, 2007). Even though computational composites compromise a detailed technical account of crafting actual smart materials, they enable rapid prototyping of a whole that can be experienced in real scale (Bergström et al., 2010).

The Role of External Representations in Design

Designers use a variety of prototyping tools to explore and communicate what it will be like to interact with a to-be-designed product. External representations, including a sketch, an interaction scenario and a physical prototype instantiate spaces for subsequent actions (e.g. through reflection and test), also embody a wide range of knowledge (e.g. aesthetic knowledge; Ewenstein & Whyte, 2007). The power of external representations in thinking and reflecting has been highlighted by many scholars (e.g. Schön, 1991; Kirsh, 2010) and across various creative processes such as writing (Neuwirth & Kaufer, 1989). External representations can be easily circulated and are crucial in establishing shared understanding among individuals of a multidisciplinary design team (Henderson, 1991; Lee, 2007). In the design situation with underdeveloped smart materials, design representations become an important source in tracing how designers might have accounted for materials experience. In addition to their instrumental role in unpacking the design processes, design representations have been considered a rich resource to design tools for designers (e.g. Newman et al., 2003; Yamamoto & Nakakoji, 2005; Dow et al., 2006).

The background on materials understanding and design representation sheds some light on the importance of dynamic and responsive qualities of smart materials, making their experiences unique from other conventional materials, being more dialogical to the environmental and behavioral context of use. Furthermore, it emphasizes the role of prototypes, as substitutions for an underdeveloped material and product in enabling direct, physical interaction, which in turn supports designers' understanding of the experiential qualities (Buchenau & Suri, 2000). It seems that the lateness or earliness of design process materials' investigation and experimentation could considerably affect designers' understanding of the space of possibilities with new materials. The design approach and the tools and techniques, used by the designers, such as material samples that represent certain qualities of the underdeveloped material and the

proposed concepts are important aspects of the design process to look into. Accordingly, by studying the design processes with LTM material through materials experience lens, we hope to;
1. Find useful clues on how the designers supported their understanding of experiential qualities
2. Identify the gap, while sketching new design tools to bridge this gap

Data Collection Method

We initiated four semester-long (i.e., 20-week-long) design projects for master's level design students, with an identical generic design brief: to design and prototype product applications with LTM materials. The students received an introduction to LTM materials which included verbal description of their *key* physical properties (i.e., thin and flexible sheet materials) and sensing/actuating functions (i.e., pressure and deformation sensing and light-emitting), supported by a schematic representation of their structure (Figure 1). The method of data collection was through participant observation (Denzin, 1973), meaning that the first author was involved in the supervisory team of the projects as a coach and had the opportunity to frequently meet with the students and get updates about their activities on a weekly basis. The students were also asked to self-report their design activities in text (e.g. online blogs) and diagrams, complementing them with photos and videos of the process. These secondary data complemented the first author's notes, taken during site visits and meetings with the students on multiple occasions. In the analysis of the design activities, we deliberately left out the quality of final concepts and instead examined how students' design activities allowed them to make sense of the abstract material information. We were particularly interested in how these activities supported the students to bridge between the information and certain application design directions, manifested though design representations. The external representations, developed and adopted by the students to support their design activities, were identified and reflected upon. Accordingly, we discussed why certain representations might be more useful than others for creation of a design Tool Kit.

Introduction to the Four Cases

The first three cases were conducted by three groups of M.Sc. design students — with each group, being consisted of six students— under Interactive Technology Design course, where iterative prototyping and working with electronics were supported and encouraged. The course was chosen thanks to its emphasis on bottom-up approach when understanding interactive technologies and designing with them. Case 4 was a graduation project, in which Vision in Product Design (VIP) method (Hekkert & van Dijk, 2011) was adopted so as to reinforce a top-down approach towards understanding of the overall effect and qualities of material/product in interaction. All students were native, with respect to LTM materials, prior to joining the projects. They were asked to conceptualize and embody meaningful applications for such underdeveloped materials, departing from identical introductions to LTM materials. The four projects finished with experiential prototypes of the proposed applications within the six-month period of the projects. Covering both hands-on approaches, using physical and digital materials and top-down processing necessary for designing meaningful applications, the four cases involved a variety of representation media to serve the specific aim of our study. The pictographs of the events along the design processes are presented in Figure 2 (the detailed descriptions of the design processes can be found in earlier publications; Barati et al., 2015; Barati et al., 2015). The four diagrams in Figure 3 illustrate the sequence of events in the design process, including pictures of the activities and the external representations, accompanied by brief explanations in black and pink boxes. The representations and tools, linked to the activities in the pink boxes, were further selected to exemplify the four types of representations, used across the cases.

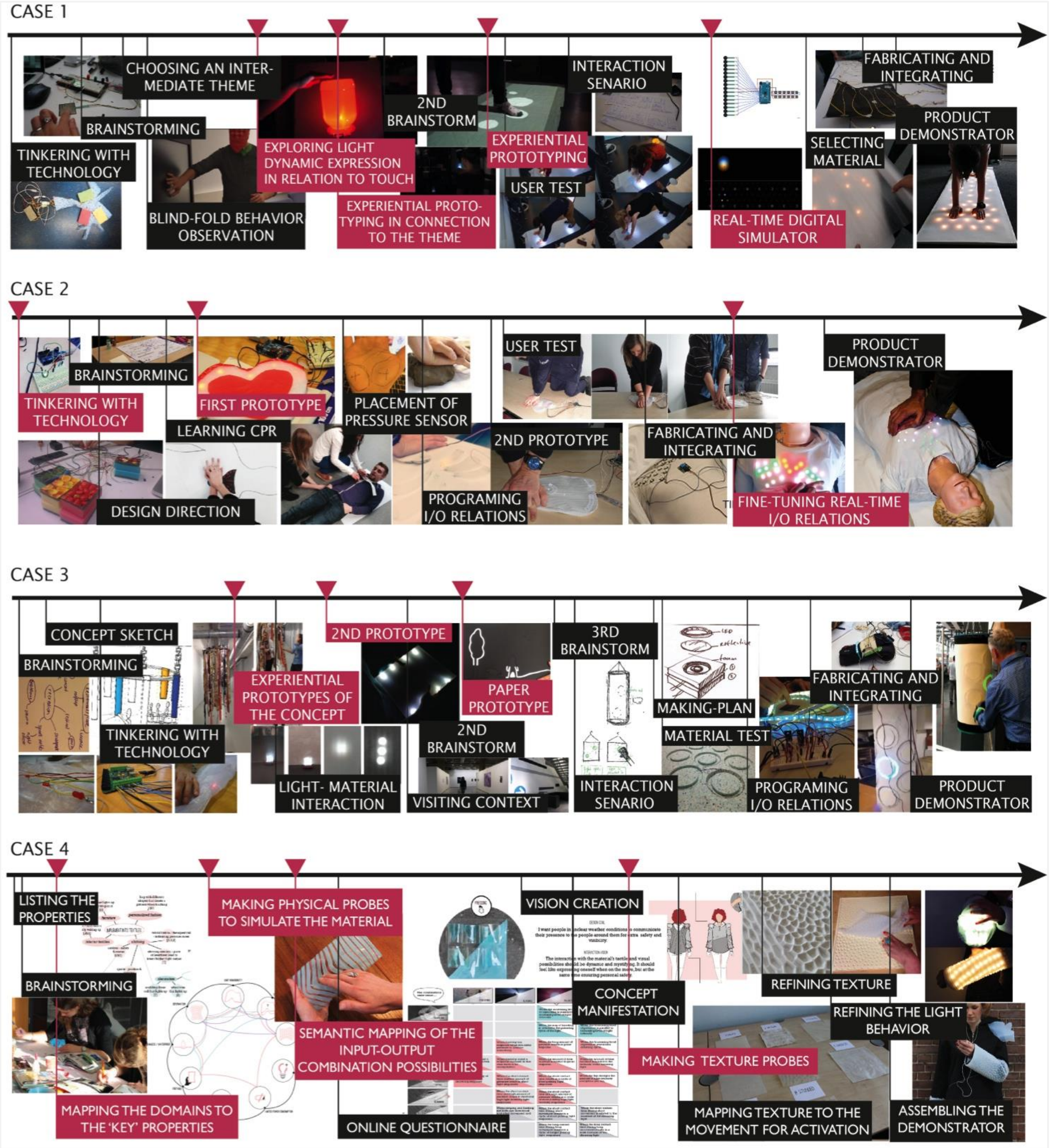

Figure 2: *The sequence of design activities — black and pink boxes— and the external representation, used in parallel to the activities over the course of the four cases — the representations associated with the pink boxes are further used to exemplify the three categories of representations, used by the students, namely design concepts, technology probes and possibility maps—*

Analysis and Findings

Even though the processes varied greatly in detail, we suspect that the design activities were mainly organized to reduce uncertainties (i.e., things that are unknown or known only imprecisely; McManus & Hastings, 2005), some of which persisted along the design processes. When compared with a conventional design process, in which (fully-developed) materials are selected to fulfill a set of design requirements, designing with LTM materials can be characterized as highly uncertain. The students' direct and indirect comments about the assignment and their experience through the process enforced this assumption. One explanation could be that in the assignment, both knowledge of the material and the constraints was fragmentary, with the design objectives and use context remaining unspecified (cf., McManus & Hastings, 2005). Another explanation could be that the design methodologies students familiar with the process, had little to offer on how to approach such open-ended design brief, departing from a specific material.

In the absence of direct access to LTM materials to test their assumptions, the verification of the materials scientist who worked with the underdeveloped material, was often necessary. In other words, their investigation of other materials could not automatically reduce the uncertainties with regard to the qualities and behavior of the underdeveloped smart material. The probes and prototypes, made by substituting materials and technologies to represent LTM materials, were suggestive of the *becoming* of the materials, rather than communicating what could be actually done to them, for instance, in terms of processing or shaping.

These findings highlight the importance of external representations and prototypes, not only in communicating the — potential— experiential qualities, but also in specifying the design objectives and constraints through discussion and debate (i.e., boundary negotiating object; Lee, 2007). Having viewed the overall approaches in the light of reducing the uncertainties in relation to unspecified context of application and the under-specified material, and having reflected on the roles and media of the representations, we further elaborated the direction and guidelines for support tools.

Overall Approach in Designing with LTM Materials

Across all four cases, familiar design activities shaped the design processes' brainstorming sessions for application ideas and possible design directions, investigation in the context of use and interactions, revisiting concepts through an iterative process, detailing the chosen concept and making probes and prototypes. In Cases 1, 2 and 3, an early attention was given to tinkering activities with digital technologies such as off-the-shelf pressure sensors and LEDs, which represented the working principle of LTM materials. Alternatively, in Case 4, the student attempted to synthesize the possibilities through mapping the brainstormed design ideas and the given set of properties. Soon deciding to simulate the LTM materials, particularly, in terms of *how they look* (i.e., physical features) rather than *how they work*. To that aim, he/she reified the schematic structure and used a polymer film of the specified thickness, keeping on the exploration of performative qualities, encouraged by those representations of LTM materials.

Our observations primarily confirmed that abstract information of LTM materials was inadequate for understanding the experiential qualities. In all cases, the student's sooner or later reified the abstract set of LTM materials' properties and structure through physical probes and tangible representation. Even though to varying extents, those representations enabled them to — temporarily— decrease material uncertainty and explore and understand the — potential— experiential qualities. The risk involved with such reifications is that they could lose sight of the fact that those physical representations are only partially representative of the possibilities. For example, by assuming that OLED and piezoelectric polymer components — which is a literal reading of the schematic structure— overlay alternative architectures (e.g. patterned overlay) entirely. Therefore, geometries, movements, and experiential qualities, emerging from them are overlooked. A closer inspection of the processes revealed four distinct strategies that may explain the differences between the cases when coping with material and context uncertainties.

1. *Case Study 1: a thematic frame*

In Case 1, we noticed a rather interesting approach in managing the uncertainties: choosing a thematic frame, *way-finding in the dark*. The frame was general enough to explore possibilities and yet connected through an activity to the basic working principle of LTM materials. It shifted the attention from *where to apply* LTM materials to the experiential qualities, in particular performative qualities, without imposing definitive commitments. Within this intermediate theme, students conducted experimental studies, such as observing behavior of blindfolded participants to understand the role of haptic feedback within navigation process. Their first prototype, a network of water bottles that lit up in succession when squeezed (Figure 3), prepared for exploration of experiential qualities that arose from various couplings between touch input and light output in the interaction.

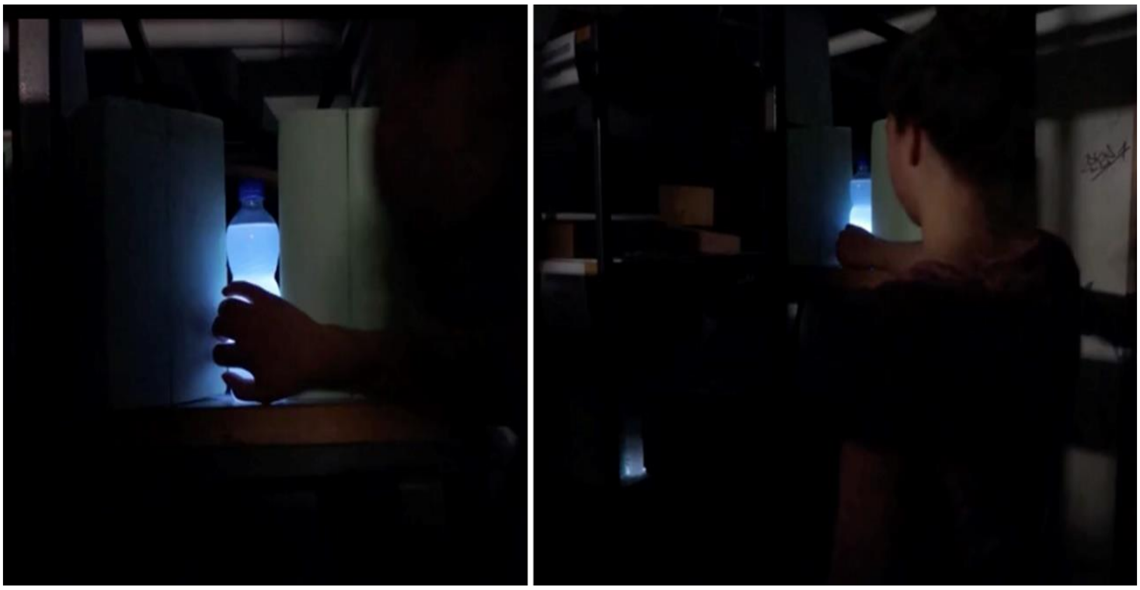

Figure 3: *Screenshots of a video showing the hybrid prototype, developed in relation to the thematic frame of 'way-finding in the dark'*

2. *Case Study 2: an established practice*

In the second case, the students' brainstorming sessions, informed by their initial tinkering with digital technologies, signaled to a definitive practice, namely Cardiopulmonary Resuscitation (CPR). The connection between pressure sensitivity and responsiveness of LTM materials and the established practice of CPR, convinced the design team about the benefits of the proposed direction. The three iterations of embodying and specifying the responsive behavior were essentially driven by the usability requirements to perform a successful CPR. Selection of established practices of Yoga in Case 1 also worked as a mitigating strategy to reduce the context uncertainties and justify the exploitation of LTM materials.

3. *Case Study 3: a fixed context and several dispersed concepts*

In Case 3, students approached the assignment more experimentally, fostering shorter cycles of iteration, each dedicated to a different concept. Having chosen *museum*, following an initial brainstorm session, they invested their time in sketching and making several physical prototypes. The dispersed concepts, ranging from *info stands* to *interactive picture frame*, varied in terms of design goal, form and even user group — adults and children—. Nevertheless, students found it difficult to convince each other as well as the material expert, associated with the LTM project, about the benefit of these concepts. Their struggle highlighted the necessity of understanding technical boundaries as a common ground and exposing the implicit engineering requirements. For instance, it became clear the concepts that did not require multiple-range and spatial pressure sensing, could be made with much simpler switches and piezoelectric sensors, hence underexploiting the LTM material. Another takeaway was that with the embedded interactive applications, *contextual* storytelling became crucial, as it involved description of the behavioral context, physical embodiment and information intersection in both time and space.

4. *Case Study 4: mix and match the elements*

In Case 4, there was a long exploration phase that resulted in physical prototypes, semantic maps of *possible* domains of application and taxonomy maps of shapes, textures, input and output modes of interaction (e.g. stroking). Having explored these elements individually and isolated from each other's effects and incorporated the findings ultimately in a composition, the student relied on a *mix and match* approach to deal with the uncertainties. Even though the clear-cut taxonomies of elements' range helped confining the student's attention to a definite group of possibilities and relations, they revealed very little about the possible effects of the interrelations between the elements in a situational whole. Such a limitation in the mix and match approach must not be underestimated, since the experiential qualities of a composition might not be sums of the experiential qualities of isolated elements.

The Representational Tools and Techniques

To capture the specific qualities of a design tool to support the understanding of LTM material's experiential qualities, vignettes of the external representations used across the four processes (pink boxes in Figure 2), were discussed under three categories: design concepts, technology probes and possibility maps. We elaborate the subcategories of *educational*, *boundary* and *generative* probes as well as *semantic and taxonomy* maps to discuss the in-situ roles of these supporting design tools. As further explained in the following paragraphs, these tools were deliberately made and used to obtain more information about specific aspects of LTM materials. Therefore, understanding their conditions and effects on understanding, exploring and communicating the experiential qualities of LTM materials would bring us one step closer to ideas for next-generation tools. Note that these categories are not mutually exclusive. Instead, they highlight one or few qualities common to a number of tools.

1. *Design Concepts*

Many intermediary representations, varied in fidelity and scale, were used in the processes to communicate specific application concepts. Figure 4 shows examples of representations, used in Case 2 and 3. In the former, a CPR training concept (Figure 4, left and middle) evolved through three iterations, which elaborated on the main functionalities (e.g. light feedback on speed and pressure), pattern and temporal behavior of the light output. Here, experiential qualities such as meaning of different light colors, aesthetics and performative qualities were specified to serve the usability measures of an efficient CPR. These concrete representations made it possible for the design team to reflect on the value and overall effects of the application early on in the process. In case of an underdeveloped technology such as LTM materials, concept representations are crucial to support discussions about the possible and *preferred* design directions.

Unlike the evolutionary representations of the CPR trainer in Case 2, Case 3 employed multiple concept representations, having little in common, besides their use context — museum—. Here, students used everyday objects to explore what physical involvement with the concepts might feel like in actual size (Figure 4, right). These application concepts hinted on the students' considerations of potential performative qualities of LTM materials, revealing for instance that thinness and flexibility of such materials had been exploited to embody the *hanging leaves*, while encouraging the act of pulling and deforming for the activation. Through formal use cues, such as making narrow and long strips of textile in a composition that resembled bead curtain, they considered possible actions — or performances— which might be facilitated, such as pulling and walking-through. Relying on symbolic resemblances, not only they linked any given properties to the interaction modes, but also intended future users to be able to decode these — potential— performances and comply with an unwritten instruction for LTM materials activation.

Figure 4: *Representations of the application concepts. Left: The first representation of the CPR trainer. Middle: The CPR trainer concept after three iterations. Right: The low-fidelity experience prototypes of info-stands for a museum*

In order to represent the dynamic qualities of their concepts, the students made use of hybrid tools. Figure 5 illustrates examples of such representations. The first example (Figure 5, left) was from Case 3, as the students used overlaying papers and backlight to represent a dynamic change of light pattern in their *interactive picture frame* concept. A similar approach could be observed in Case 1, though this time the students used light projection to augment an ordinary Yoga mat (Figure 5, right). In both cases, the hybrid tools were employed following the decisions about potential use contexts.

Figure 5: *Two different hybrid tools to communicate dynamic qualities of the design concepts. Left: Backlight and perforated paper. Right: Projection in combination with a physical mat*

2. *Technology Probes*

The category of technology probes identifies small investigations through substitution of technologies and materials in order to gather information about different aspects of LTM materials, such as engineering and experiential qualities. These instrument probes were deployed to find out the unknown and — hopefully— to return with useful or interesting information (Hutchinson et al., 2003). Examples of technology probes, developed and used for designing with LTM materials which emphasized there in situ roles, are discussed under *educational*, *boundary* and *generative*.

The tools such as Arduino platform, compatible off-the-shelf components such as sensors and ready-made scripts provided by technical support, to understand the basics of programing played an important role to understanding interactive — digital— aspects of LTM materials, particularly the relation between pressure input and light output. Thanks to these tools, students managed to develop educational probes. For example, in Case 2 students were capable of building a simplified version of a pressure sensor, using beer bottle caps and sponges (Figure 6). Sundström et al. (2011) highlighted the importance of what they referred to as *educational bits* in understanding the basics of digital materials such as Bluetooth and RFID. Similarly, the students' initiative to grasp the working operations through making such simple construct highlighted the educational role of the probe. Using educational probes through low-tech prototyping facilitated a shared understanding of LTM materials' working operation within the group, prior to proceeding with the application conceptualization.

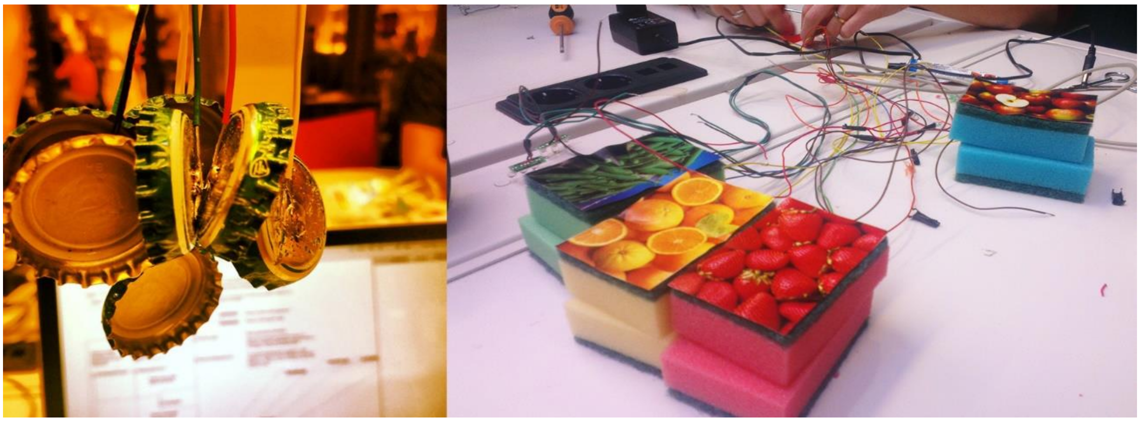

Figure 6: *A simplified pressure sensor, made with beer bottle caps and sponges*

The second subgroup of technology probes, used across our cases, was developed to specify the technical boundaries of LTM materials. For instance, in Case 4 the student used a thin and flexible sheet of polymer that more or less mimicked the physical properties of OLED component to create a library of shapes (Figure 7). Showing a group of objects to the material expert, he/she inquired about the possibilities and limitations of the technology itself, as well as an understanding of the important boundaries. For example, using these physical probes, the student gathered specific information about the bending radius of OLED. He/she realized for instance that the dynamic movements that involved bending below a certain radius would be technically challenging with the current OLED processing techniques. On a similar note, Sundström et al. (2011) used the category of *boundary bits* to specify the limits of technology, so the design team could avoid them before proceeding with a design conceptualization.

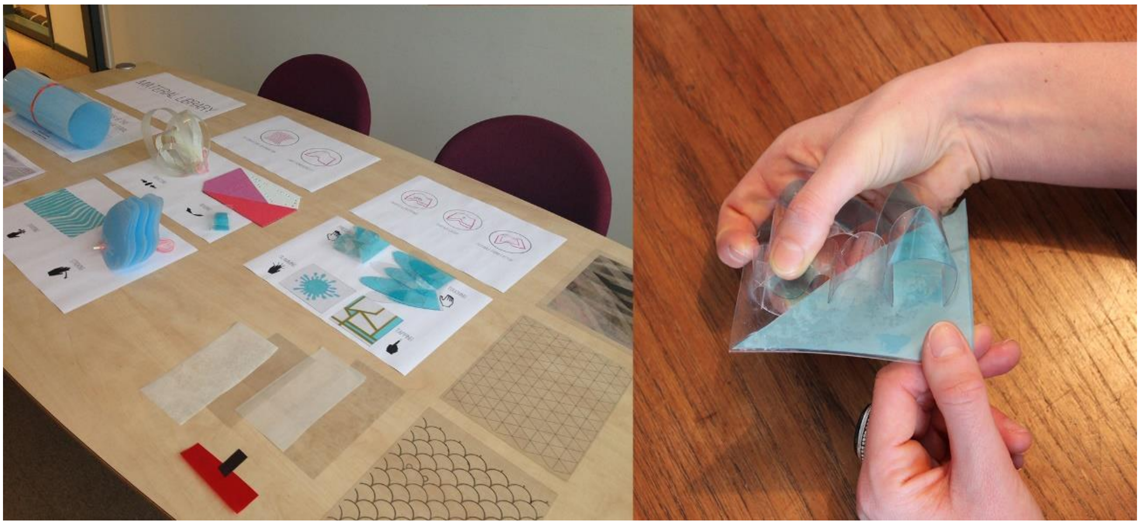

Figure 7: *The physical probes, used in Case 4 to further specify the design boundaries. Left: A setting in which the probes are shown to the material expert. Right: A close-up*

In Case 1, the students explored the interactions more constructively but less systematically, using what we annotate as *generative* technology probes. With their Wizard of Oz technique, they assembled a lamp under a bottle, filled with milky liquid and a dimmer — a slider input device—. Using this probe, not only did they approximate the dynamic experiential qualities of LTM materials, but also supported multiple manifestations simultaneously. The generative quality of the tool, when combined with video recording — using a mobile phone— allowed for both exploring and reflecting on several couplings between dynamic light and touch (Figure 8, right). Another instance of generative tool was at a later stage of the design process, when the students used Adobe Flash, to make a real-time program to specify and optimize the light expressions of their Yoga mat concept (Figure 8, left).

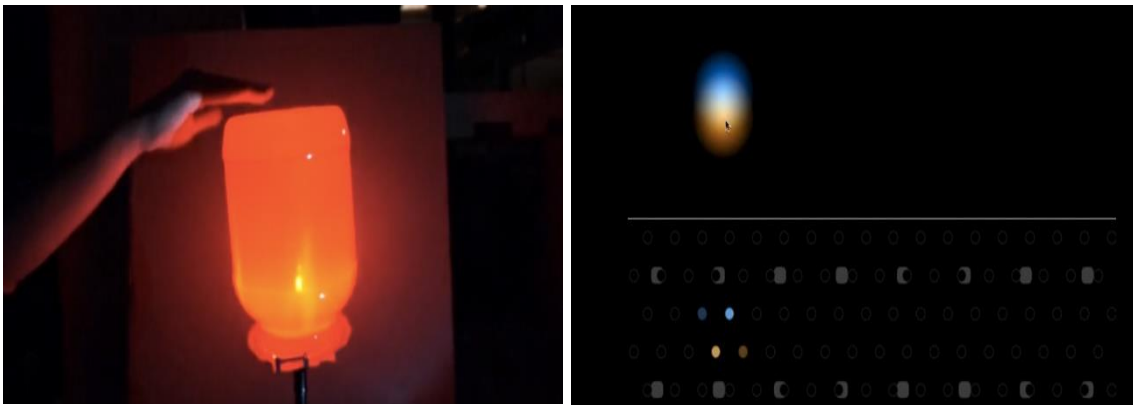

Figure 8: *Screenshots showing how some design representations enabled multiple manifestations of the dynamic light, using a dimmer input device (right) and a program that converted movement of the mouse to dynamic light*

3. *Possibility Maps*

The third category of representations, used mainly in Case 4, could be labeled as *possibility maps*. These maps contained images of the material samples, developed by the student and pictograms of the known material properties. Their purpose was to support the student explore the interaction and application possibilities of LTM materials. The visual organization of the material information and the developed samples on a single sheet enabled the student to look into the relation among the qualities, prior to getting narrowed down to specific application directions. For instance, as shown in Figure 9, the student tried to capture taxonomies of input-output combinations and textures (Figure 9, middle), using both material samples and categorical qualitative labels (e.g. breathing light). The latter was further used to explore the potential experiential qualities, at interpretive and affective levels (e.g. combination of *stroking* and *pulsating* might be experienced as *lively* or *boring*). In addition to the taxonomy maps, the student developed another form of possibility maps, linking combinations of the given material properties to a variety of product categories. These semantic maps, such as the one shown in Figure 9 right, helped the students reflect on and select the appropriate application design directions.

Figure 9: *Extensive use of words, mainly adjectives, to represent the variety of input-output modes (left) and textures (middle). Right: An example of the semantic maps, used for synthesis of the application domains in relation to the properties*

Discussion

The case studies revealed four different approaches in response to design assignment. Choosing an established practice was an efficient strategy to cope with material and context uncertainties as well as yield early functional prototypes with clear utility. One side effect was that the students did not spend on material exploration and understanding of aesthetics, expressions and performances in relation to material properties and structure. Our observation of the processes suggested that through early prototypes of their concepts as well as material and technology probes, students tried to understand sensorial and performative qualities of LTM materials. Nevertheless, initial assumptions about the experiential qualities were triggered by the given information, uncovering the traces of *analogical reasoning* (e.g. like a paper sheet; Ball & Christensen, 2009) and reusing *episodic knowledge* (e.g. a personal CPR experience; Visser, 1995). Anecdotes of referring to affective, interpretive and performative qualities appeared prior to probe making and prototyping, during the first brainstorming sessions. For instance, from a combination of thin and surface lighting, students assumed that LTM material could elicit experiential qualities such as *surprise* — affective level— and *high-tech* — interpretive level— or could be *deformed like a paper sheet* — performative level—.

Making material and technology probes along with application prototypes helped students test their assumptions about the experiential qualities, revise them and form new assumptions, triggered by multi-modal interactions (Wendrich, 2012). Our observations of Case 4, as the only case not to involve multi-media probes and prototypes early on, revealed that language (e.g. descriptive and qualifying adjectives) was used extensively in exploration of the experiential qualities (e.g. via asking participants about combinations of *squeezing* and *flashing*).

Even though such explorations were supported by means of detailed physical probes, the participants — in the students' multiple-user studies— had to imagine the dynamic and interactive qualities of LTM materials with the help of adjectives and static pictures. When combined with single-medium representations of an underdeveloped smart material, this highly-linguistic approach can only partially reveal the potentials. To prevent static and limited understanding of the experiential qualities and facilitate multi-modal experiences of LTM materials, multi-media tools and representations should support the explorations early on in the design process. Analyzing the four cases, we identify two limitations relevant to the exploration of potentials in designing with LTM materials;

1. Reifying the material concept without reflecting on the actual design variables (e.g. what does the schematic structure represent in terms of open design variable?)

2. Early fixations of the intended experiential qualities in accordance with the requirements derived from a chosen context, rather than exploring and exploiting experiential qualities, derived from material properties and structure

As the only certain source of information about LTM materials, the initial descriptions and representation were expected to greatly affect the way of potentials' interpretation (Orlikowski & Gash, 1994) and requirements were to be determined (Davidson, 2002). Nonetheless, multiple other factors could have played a role in the extent the possibilities were explored and exploited, such as personal and group motivation, ambiguity of the information regarding the degrees of freedom and incompatibility of the representational tools and LTM materials' sensorial qualities. We believe that to encourage opening up the possibilities, beyond what could have been imagined for a specified technology, the representations should allow for exploration of *what LTM materials could be* and *could do*, rather than merely *what they are* and *do*.

An observation across the cases revealed that even though the students tried to capture the complexity of LTM materials in their representations — the extent varied across the cases— none of the representations allowed them to approximate the experiences of interactive thin and flexible structures. We suppose that the practical limitations of their chosen tools in representing combinations of dynamic movements, sensing and dynamic light output did not favor a higher-fidelity approximation of the — potential— experiential qualities, particularly at performative level. The various representations, employed across the cases, suggested that the students did not give equal attention and treatment to the given information about physical and digital aspects of LTM materials. Clearly, digital qualities of LTM materials played a more dominant role in determination of high-order functions of the applications (e.g. light feedback to notify the next Yoga pose), while the physical properties defined low-order details (e.g. flat and portable). As highlighted by Giaccardi and Karana (2015), physical properties of the material can play a more *active* role in how habitual practices around a material are shaped. Accordingly, understanding — and reflecting on— the physical and digital blend of LTM materials in relation to the active roles they play in unfolding and transformation of practices might lead to new possibilities. Given our particular focus on supporting an understanding of the experiential qualities and the limitations discussed above, our future work will focus on high-fidelity representations of LTM materials, which;

- Enable simultaneous experiences of physical and digital aspects of the components and compositions
- Elaborate on currently overlooked material variables, such as structure and processing, as well as their roles in opening up possibilities unique to these yet underdeveloped materials

In the final section of this paper, we shall sketch our twofold approach to produce these higher-fidelity representations of LTM materials. The approach is partly inspired by our findings of adopted probes and representations, and partly informed by recent material-centered approaches in product and interaction design literature.

Implications towards a Tool Kit

Dynamic properties of LTM materials, pertaining to physical properties (e.g. elasticity) and composite structure, can be used to create emotional expressions and performative character (cf. Niedderer, 2012). Furthermore, these dynamic movements can be combined and coupled with temporal and context-dependent light expressions. One part of the Tool Kit should aim at making these complex dynamic qualities of LTM materials experiential through multi-media representations. A promising representation can be created through the combination of materials and projection in order to experience the physical and digital aspects of LTM materials simultaneously. Projection has been previously used in a multi-media design tool to design consumer products, by changing the appearance digitally and reflecting on a product at hand to see the ultimate effect (Saakes and Stappers, 2009). It can allow for simulation of the illuminate surface, dynamic light expressions and augmentation of physical objects, representing thin and flexible embodiment of LTM materials. Another promising technique is Chroma key, a video editing technique widely used in filmmaking industry. One important consideration in conceptualizing this part of the Tool Kit is its adaptation to different design contexts, given our findings that the entries to the process of designing with the LTM material can vary.

Another part of the Tool kit should focus on explication of material variables (e.g. components, structure), boundaries and relations. Such understanding is a necessary step for designers to grasp what can be done with the material and the degree of freedom in manipulating it. In addition to concept representations, our analysis highlighted that *boundary* probes were particularly used to verify specific knowledge about LTM materials. Researchers have extensively talked about the role of external representations when explicating and even negotiating the boundaries in multidisciplinary projects (e.g. Star & Griesemer, 1989; Boujut & Blanco, 2003; Lee, 2007). Theoretical concepts such as *boundary objects* (Star & Griesemer, 1989) and *intermediary objects* (Boujut & Blanco, 2003) are proposed to support a better understanding of the design representation's role in cooperative work. Our findings about the students' assumption of the structure as a fixed variable, peripherally hinted at the limiting influence of the given structure schematic. To avoid such limitation and possible misunderstanding of the representations for information, it seemed necessary not to think of them as representative of multiple representations — accompanied by additional explanations—.

Emphasizing that in working with new interactive materials, material understanding should be considered in earlier phase of the design process, we encouraged designer's active involvement in material explorations. A designer-like way of understanding materials through hands-on manipulations and processing can complement and tease the dominant technical objectives for which early samples were made (e.g. Franinović & Franzke, 2015; Barati et al., 2019). Working directly with smart materials can provide insights to material-related design variables along with their influence on — potential— experiential qualities (Karana et al, 2015). Aiming at a better understanding of these variables, we could fabricate electroluminescent materials, as a representational smart material for OLED component. Similar hands-on approaches have been advocated in the *understanding step* of Material-Driven Design method (Karana et al., 2015), and have been deployed in works of Olberding et al. (2014), Franinović and Franzke (2015), and Barati et al. (2019) to fabricate novel electroluminescent samples. The experimental study approach fills in as a proxy between material science and design practice to support understandings of LTM materials.

Conclusion

Through four design case studies, we gained a better understanding of design approaches and the representations relevant to the experiential qualities of LTM materials. Our analysis revealed many useful design initiatives that can potentially mitigate the challenges of understanding an underdeveloped smart material as well as its potentials. In addition, the limitations of current approaches and tools were discussed to give rise to a future Tool Kit.

The elements in the Tool Kit were considered to serve its two-fold purpose;
1. To enable simultaneous, multi-modal experiences of physical and digital aspects of LTM materials
2. To elaborate on material variables, such as structure, processing and their role in relation to experiential qualities of LTM materials

The implications and suggestions, arisen from the case studies, as well as the literature, could support us move towards better realization of such a Tool Kit.

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