Dynamic Experiences Generated by Sensory Features Through Smart Material Driven Design

MARTA GONZÁLEZ-COLOMINAS
Elisava, Barcelona School of Design and Engineering

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Materials can be considered the interface of a product as they mediate between user, environment and object (Karana, Pedgley and Rognoli 2014). They characterize the physical world and generate a continuous flow of sensory interactions. In this age of mass production, engineers and designers are in a unique position to use the opportunities presented by materials development and apply them in creative ways to trigger meaningful user experiences.

Dynamism is considered a very promising material experience in terms of creating meaningful interactions, and, consequently, user attachment to a product (Rognoli, Ferrara and Arquilla 2016). Dynamic products are those that show sensory features that change over time in a proactive and reversible way, activating one or more user’s sensory modalities and aiming at enhancing the user’s experience (Colombo 2016).

Smart materials could be considered the most suitable candidates to provide dynamic experiences. They react to external stimuli, such as pressure, temperature or the electric field, changing properties such as shape or colour. They are capable of both sensing and responding to the environment, as well as exerting active control of their responses (Addington and Schodek 2004). Compared to understanding traditional materials, smart materials involve additional technical complexity.

The aim of this paper is to share how the Material Driven Design (MDD) method (Karana et al. 2015) has been applied and to analyse a set of 10 projects, grouped into 5 case studies, developed by students from ELISAVA over the last 3 years to improve ways to implement the method. We have analysed the case studies in terms of the changes observed in the sensory features, using a sensory map proposed by Sara Colombo (Colombo 2016). By comparing different projects, the paper shows how the sensorial aspects are invoked by different smart material properties.

The 5 case studies have integrated the smart materials into functional prototypes for different application sectors, such as healthcare, energy harvesting or fashion. We have found that only three sensory modalities (sound, sight and touch) were involved in the user experience, with sight being the most predominant sensory perception.

This study aims to serve as a springboard for other scholars interested in designing dynamic products with smart materials.

1
INTRODUCTION

The functionality of a product is not the only factor that determines consumption today. Indeed, there is growing interest in the more intangible side of products (Karana, Hekkert and Kandachar 2009). Researchers have demonstrated that an emotional connection between the user and the product increases the user's attachment to the product (Ceschin and Gaziulusoy 2016). Different design strategies have been proposed by several authors to stimulate product attachment (Chapman 2005; Ceschin and Gaziulusoy 2016). Materials can determine whether the user's experience is pleasing or displeasing (Jordan 2002), due to the fact that they have morphological characteristics, such as function, expression and structure.

'Materials experience' refers to the active role of materials in conditioning and influencing our experiences with and through materials (Karana, Pedgley and Rognoli 2014). Conceptualising a meaningful material application requires a careful understanding of the experiential qualities (Karana et al. 2015). The materials experience explanation is founded on the idea that the mutual interaction between product and user is what creates the particular material experience (Giaccardi and Karana 2015).

Dynamism is considered a promising material experience in terms of creating user and designer attachment to a product (Rognoli 2015). Dynamic products are those that show sensorial properties (visual, tactile, auditory and olfactory), which change over time in a reversible way, and aim to enhance user experience (Colombo 2016). Traditionally, products have a static appearance. However, dynamism breaks the monotony of the relationship usually established between user and product (Rognoli 2015). Our first interaction with materials takes place at the sensory level. Emotional experiences are triggered in the first stage by sensory stimuli and this sensorial component of experience is inevitable (Giaccardi and Karana 2015). As Sara Colombo asserts (Colombo 2016), dynamic products should be achieved carefully. A high number of dynamic products would provoke a confusing sensory overload.

Very few researchers have investigated dynamic products in shape-changing interfaces. Sean Follmer and collaborators (Follmer et al. 2013) have explored the possibility of using dynamic shape changes on actuated displays. Hyunyoung Kim and collaborators (Kim, Coutrix and Roudaut 2018) have analysed a set of 82 reconfigurable everyday objects to discuss how they could inspire the design of reconfigurable interfaces. The authors define reconfigurable objects as those objects that embed reconfigurations and shape-changing features. A shape-changing object is a dynamic object with changing visual and/or tactile features. However, in this study, the term dynamic object is not limited to shape-change: it includes all sensory or feature changing objects such as those related to colour, light or temperature, for example.

In dynamic products, smart materials play an important role thanks to their ability to transform energy, adapt to the environment and/ or change their properties in response to external stimuli. In addition to their passive function, they provoke an active reaction, such as changing shape or colour (Ritter 2007; del Corral et al. 2016).

Technological advances, in combination with smart materials, are changing the way of thinking and designing the interaction between products and users. The development and application of smart materials has been necessary due to the desire for more automatic and compact systems and products and the rising demand for energy sources (Ritter 2007). Their novel and unexpected properties have great potential to surprise and generate interest and fascination, when used in an appropriate context (Rodríguez 2014). A reaction of surprise can be beneficial for the designer because it can capture people's attention and can be a successful product differentiation strategy to distinguish a product from others (Derbaix and Vanhamme 2003). Users benefit by being able to learn something new about the product and the element of surprise makes the product more interesting to interact with.

The additional technical complexity of smart materials implies that the image of the material and its datasheet are not sufficient for the designers to use them. Designers should be aware of the impact that sensory features have on user experience. However, in product design education, there seems to be a lack of attention towards the sensory aspects of user-product interaction. This attention lacks where education is more directed towards the technical aspects of design (Colombo and Rampino 2013). Many design researchers emphasize the importance of hands-on learning in supporting an understanding of smart materials (Barati, Karana and Foole 2017; Barati, Giaccardi and Karana 2018)

The occurrence of new materials implies that design engineers are continually testing their material selection skills. The difficulty of standardising smart material properties is high, so design engineers must experiment with them to better understand their performance, thus integrating them into functional prototypes.

The aim of this study is to share how an existing method has been applied and to analyse the results through 5 case studies to improve the way it is implemented. To this end, we have created a visual table of commercial smart materials that the students have used as a design tool. We have analysed a set of dynamic products developed in ELISAVA as case studies to further understand how sensorial aspects are invoked by different smart material properties.

2
METHODOLOGY

The collection of dynamic products, presented in this paper as 5 case studies, was carried out by collecting 10 projects which use smart materials that were designed by students from ELISAVA over the last 3 years. Of the ten projects presented, seven were developed during the second year of the degree in Engineering in Industrial Design. The other three were carried out during the fourth year.

We have followed the existing Material Driven Design (MDD) method (Karana et al. 2015). It consists of

	Second year of the degree	**Fourth year of the degree**
Project approach	Smart material as the starting point. MDD method	Problem to solve as the starting point
Subject	Materials Selection	Final Project Degree
Duration of the project	10 weeks	10 weeks
Number of students	21 students	3 students
Process	Visit to Materfad, the Material Center of Barcelona. Interaction with smart materials (2 hours, week 1) Workshop. Hands-on sessions with smart materials (2 hours per week during weeks 2-4) Weekly meetings with the students. Prototyping with smart materials (2 hours per week during weeks 6-10)	
Results	7 projects	3 projects

Table 1. Methodology scheme.

three main perspectives: first, take a particular material as a starting point and explore its technical/engineering properties to embody a product; second, designing for material experiences; and third, emphasising hands-on experiments and prototyping with materials.

Regarding the first perspective of the MDD method, we have used smart materials as starting points in 7 of the 10 projects, those developed during the second year. For the other three projects, the problem to solve was the starting point and smart material selection was made thanks to the knowledge acquired during the previous years.

Concerning to the second perspective of the MDD method, we have designed for dynamic material experiences. The dynamic experiences have been classified depending on their functionality into four different categories: consciousness, operative, expressive and communicative functions.

Regarding the third perspective of the MDD method, some workshop sessions were organized to provide hands-on experience and prototyping with the materials (Figure 1). We have collaborated with Materfad, the Material Center of Barcelona, which boasts a physical database of more than 5,000 innovative materials (Peña 2008). Materfad meets the need to touch, smell, hear and feel the materials.

We have classified the commercial smart materials from Materfad into a visual table (Figure 2), to facilitate student and practitioner selection of smart materials. This study has focused exclusively on active smart materials, which are characterized by the fact that they can transduce their stimuli energy into other forms of energy. The active materials have been divided into five typologies: chromoactive, energy harvesting, luminescent, shape memory and phase change materials (Ritter 2007). Chromoactive materials have been divided into photochromic, thermochromic and electrochromic; energy harvesting materials into piezoelectric and thermoelectric; luminescent materials into photoluminescent and electroluminescent; shape memory materials into metals, polymers and foams. Phase change materials (PCM), on the contrary, don't present any subcategory.

Finally, the case studies have been analysed through a map of dynamic experiences, classified based on the stimuli and the sensory modalities they activated (Colombo 2016). The stimulus is the variation of one feature of the product (the shape, the light, the colour, the sound, the smell, the temperature, etc), as perceived by the senses (Colombo, Gorno and Bergamaschi 2013).

Two experts in materials and design have done the analysis of the sensory modality and the dynamic experience functionality. If the analysis was different, a third expert helped in making the decision to reach a consensus. To obtain more information about the sensory modalities that were more frequently employed, all projects were represented in the same sensory map with a degree of transparency, so that the overlapping of more products produced a darker area on the map.

3
RESULTS AND DISCUSSION

The results of the products proposed by the students are shown below and have been numbered from (1) to (10). Three of the products were developed during the fourth year, numbered (2), (4) and (10). The other seven projects were developed by second year students. The results have been organized by the typology of smart material used in the project: chromoactive, luminescent, energy harvesting, shape memory and phase change materials.

3.1. Case study 1 - Chromoactive materials

Raincoat & Lolita (1) is a coat that changes from translucid to opaque black with a decrease in temperature with rain or snow (Figure 3). A typology of chromoactive materials, called leuco dyes, has been applied to generate a random visual experience of shapes and colour changes, the aim of which is to be poetic and sensorial.

Through a pictorial strategy, the authors want to narrate the reciprocal action of our body with a weather phenomenon. The piece of clothing serves as a canvas that intends to reveal an experience in exaltation to rain and snow. The garment can engage its wearer in cities were the bad weather is the norm, by transfiguring this perspective into a positive interaction.

COCOON (2) is a personal protective equipment against Ebola virus, easy to put on, comfortable and simple

Figure 1. Experimentation with thermochromic inks during a hands on workshop

to take off without contamination (Figure 4). The suit has a hydrochromic coating that changes colour when wet. This coating has a communicative purpose and stimulates sight by changing its colour when exposed to fluids.

The use of the smart material helps users and other workers feel safe as contaminated areas are visible and they can therefore take special care when taking off the suit. As a result, the medical staff could be warned if a member of the team is infected.

It represents one of the two problem-based projects where the problem to solve was the starting point. Thanks to skills previously acquired, the students could take advantage of the potential of the smart materials employed and explore them in this project.

3.2. Case study 2 - Energy harvesting materials

Drums to go, D2GO (3), is a do it yourself (DIY) electronic drum that works connected to a computer with a drum software program (Figure 5). It incorporates piezoelectric materials which serve as pressure sensors, thanks to the piezoelectric effect that converts changes in pressure into an electrical charge. The material makes no sound when it is touched. The sound is digital and comes from the computer.

To accomplish an operative function, an acoustic experience is generated starting from a tactile input. When the user hits the drums, an electrical impulse is generated and converted into a drum sound.

STEP-LUX (4) is a tile that uses piezoelectric materials to transform the mechanical energy produced by pedestrians into electricity (Figure 6). This energy can be consumed instantly, as done in this project, or it can be stored in a battery. This system can be implemented into any kind of floor, pavement or asphalt.

It uses piezoelectric materials and generates 22 mW per impact. Pedestrians generate a dynamic visual experience based on a LED lighting system that is activated thanks to the piezoelectric materials.

In this particular case, the aim of creating a visually engaging experience was consciousness to change people attitudes by encouraging the use and exploration of renewable energy resources. The material also has an operative function which is generating electricity.

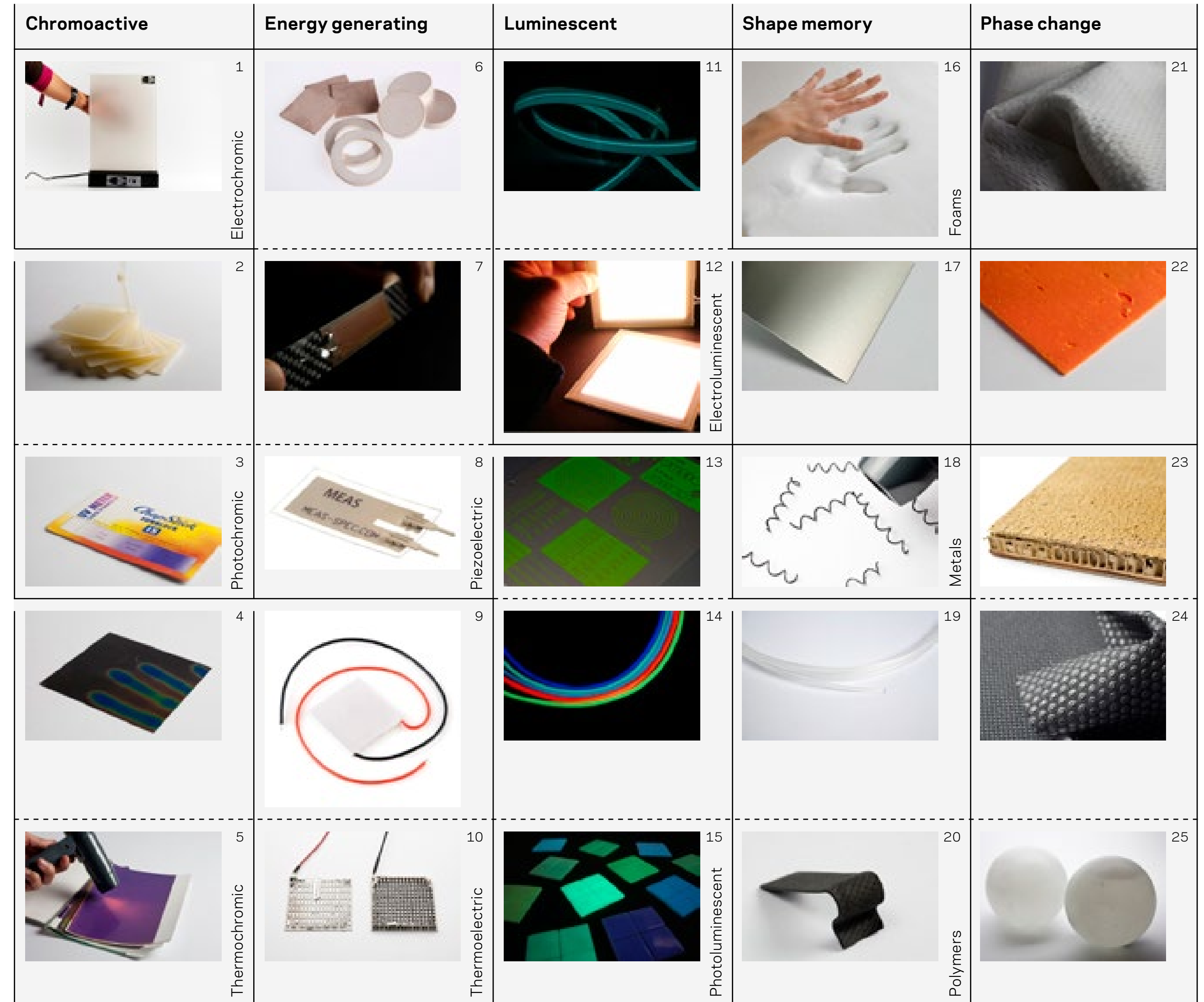
3.3. Case study 3 - Luminescent materials

HEKA (5) is a wearable product for volunteers in refugee camps (Figure 7). The garment assumes a dynamic quality that can be controlled by the user. There are electroluminescent lights integrated in the front and rear parts of the jacket. These lights are thin, flexible, wearable, lightweight and manufactured through printed electronics.

The use of coloured lights explores the possibility of communicating messages to other people through changes in the product's features as an alternative to common interfaces. This piece of clothing provides an alternative way of communication among workers, thus reducing conflicts and improving task efficiency.

HEKA has some advantages, such as communication through dynamic features being more engaging. Nevertheless, a drawback is the lack of precision in the message depending on the communication distance.

ARMOUSS (6) is a protective suit for motorcyclists with integrated materials and technology for safety purposes (Figure 8). The protective suit has integrated fabric pressure sensors and electroluminescent lights that light up in the case of an impact. The electroluminescent light smart materials have a visual communicative purpose.



01 - DreamGlass. Electrochromic glass with liquid crystal.
02 - Reversacol. UV-activated photochromic ink.
03 - SolarZone. Photochromic inks and resins.
04 - Microencapsulated Liquid Crystal.
05 - Thermocolor. Films that change colour with temperature.
06 - Customised piezoceramic components.
07 - DuraAct. Flexible piezoelectric transducer.
08 - PVDF flexible piezoelectric polymer.
09 - Square thermoelectric cell.
10 - Thermoelectric cell power generator by temperature gradient.
11 - Light Tape. Electroluminescent tape.
12 - OLED. Organic layer light panels.
13 - Blaze. Phosphorescent pigment for graphic finishes.
14 - Lunabrite Trim. Photoluminescent tube.
15 - Starlight Mosaic. Photoluminescent mosaic.
16 – Shape memory foam.
17 - Nickel-Titanium superelastic sheet.
18 - Nitinol. Nickel-Titanium alloy with shape memory.
19 - Essemplex. 3D printing polymer filament with shape memory.
20 - Veritex. Polymer composite with shape memory.
21 - Comfortemp. Non-woven thermoregulating textile.
22 - Micronal PCM. Temperature regulating additive.
23 - PCM Passive Element. Clay panels with PCM.
24 - Schoeller–PCM. Fabric with PCM.
25 - STL TN.00. Macrocapsules with PCM.

Figure 2. Visual table of smart materials from Materfad, Material Center of Barcelona, classified into five categories (Materfad 2018).

ARMOUSS helps riders become more visible. It could solve the current need for improving the visibility of motorcyclists after dark, especially if an accident occurs at night and the rider is far from the motorcycle.

3.4. Case study 4 - Shape memory materials

SAO (7) is a tea infuser with time control. It uses a shape memory spring that closes when it is in contact with boiling water (Figure 9). The time control property is embedded in the shape memory material. The spring translation movement has an operative function as it indicates the brewing time for tea. SAO also squeezes the tea leaves at the end by closing the spring.

The dynamic experience has two functions, one communicative (time control) and one operative (squeezing).

CÀLID (8) is a thermoactive container. It is served cold and changes its appearance through an opening movement when pouring hot preparations into it (Figure 10). The container is made of a silicon body with a shape memory skeleton inside. The container moves within a predefined shape without using electrical mechanisms.

It attempts to put the focus on a feeling and an emotional experience with an expressive function, changing dynamically for aesthetical reasons and ensuring a surprise effect when the product opens.

Hexafragma (9) is an automatic solar powered window blind that opens and closes with sunlight. It includes a shape memory spring that changes shape when heated and closes a patchwork of Hexafragma modules which are attached to the external face of the window (Figure 11). This allows the blind to adjust itself automatically without using electrical mechanisms and contributes significantly towards reducing energy consumption by regulating incoming sunlight into a building's interior. Another advantage in the use of shape memory alloys is that they offer a simpler design. The number of mechanical components of the actuators that use these materials is considerably inferior to the number of mechanical components contributing to electromechanical actuators (Burman, Møster and Abrahamsson 2000).

The visual dynamic experience, consisting in this opening movement, has two functions: one operative, to make the product work, the other, consciousness, enhancing users' sensory experience and inviting us to reflect on the field of energy saving.

3.5. Case study 5 - Phase change materials

PCM Soil-less crops (10) are a design solution for a root zone heating system in Mediterranean greenhouses (Llorach-Massana et al. 2017), as seen in Figure 12. They are based on thermal energy storage with phase change materials (PCM). Root zone heating systems make it possible to increase crop quality and productivity, despite the fact that they are based on the use of non-renewable fuels. PCM materials are of great interest due to their capacity to increase energy efficiency for the systems and reduce their dependence on non-renewable resources. The smart material used aims at reducing peak temperature changes through passive heating systems, eliminating the need of an electrical device.

The dynamic experience generated by phase change materials is the storage and release of thermal energy during the process of melting and freezing, changing from one phase to another. The dynamic appearance has two functions, one operative, the other, consciousness, inviting us to reflect on the field of energy saving.

This is the second example of problem-based projects in which the problem was the starting point.

3.6. Comparison between case studies

The case studies have been summarised in Table 2 and classified based on the smart material typology, the sensory modality and the dynamic experience functionality (consciousness, operative, expressive and communicative functions). The consciousness function is based on encouraging people to change their behaviour, such as saving energy and promoting renewable energy sources. The operative function is the dynamic experience necessary to make the product work. The expressive function shows dynamism for aesthetical reasons more focused on feeling and emotional experiences. The communicative function is oriented towards communicating messages to users through sensory features.

All the projects have been represented in the same sensory map (Figure 13) and the sensory modality results have been summarised in the first column of Table 1.

The results highlighted that sight is the most employed sense to design dynamic experiences. Sight is our dominant sensory system, which collects nearly 80% of human beings' sensorial impressions (Sayadi, Mobarakabadi and Hamidi 2015). In four of the projects, the user was wearing the product (1, 2, 5 and 6) and in all of them, the dynamism was based on visual stimuli (light and colour). Only a few projects used tactile and auditory sensory modalities, whereas smell was not used at all.

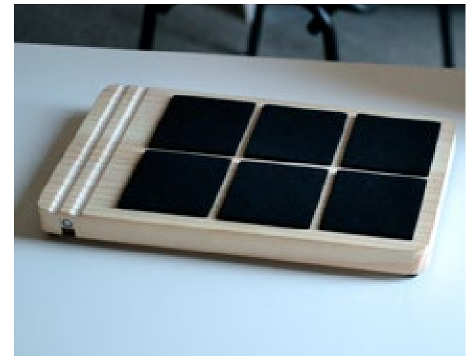
The functionality of the dynamic experiences has been summarised in the last column of Table 2 and the smart material typology has been marked in the third column of the Table. The dynamic experience had consciousness in three of the projects, (4, 9 and 10) and each one corresponded to a different smart material typology.

The dynamic experience had an operative function in half of the projects (3, 4, 7, 9 and 10). All smart material typologies were represented with the exception of luminescent.

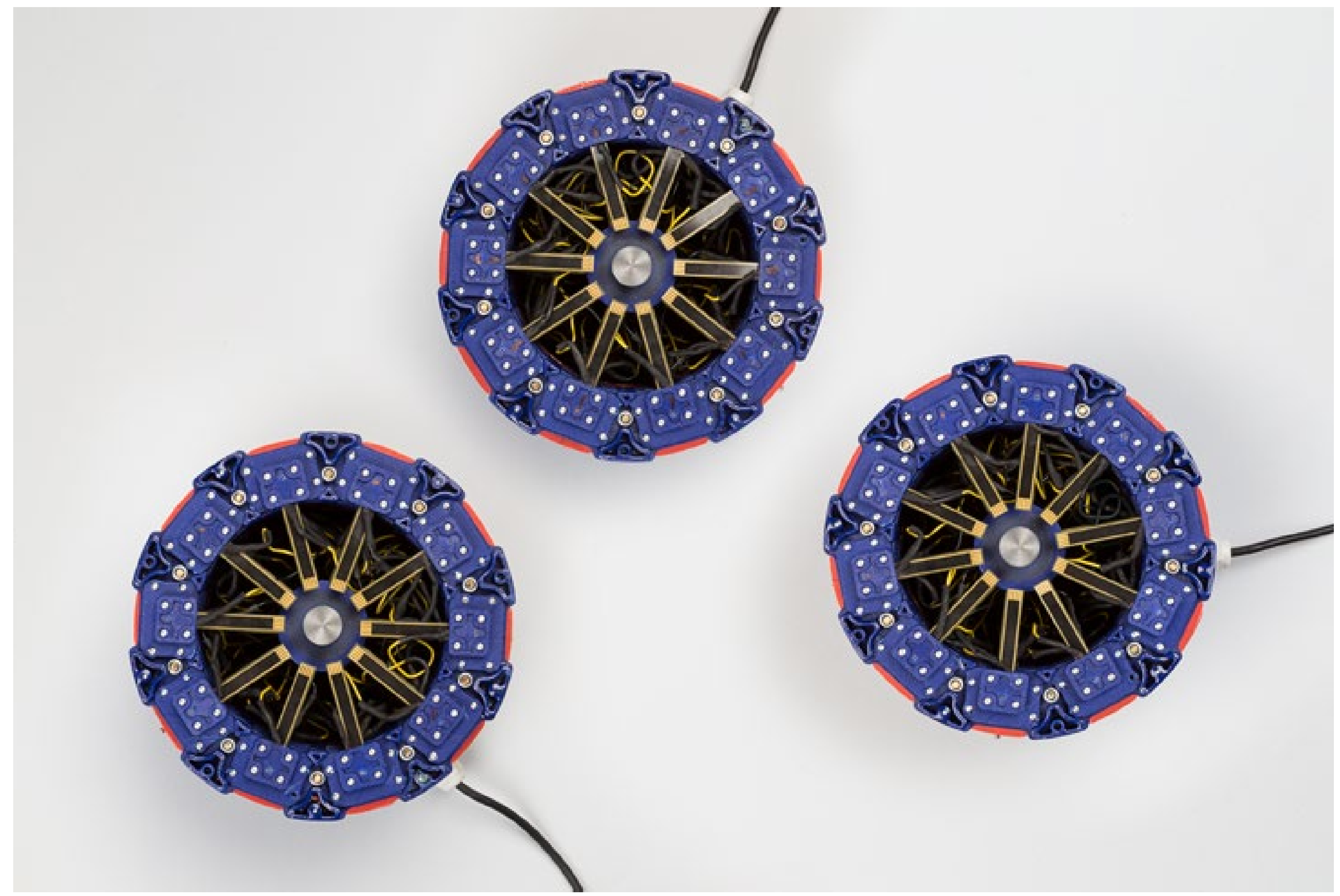
The expressive function was present in only two of them (1 and 8), each from a different smart material typology. In both projects, the only sense involved was sight.

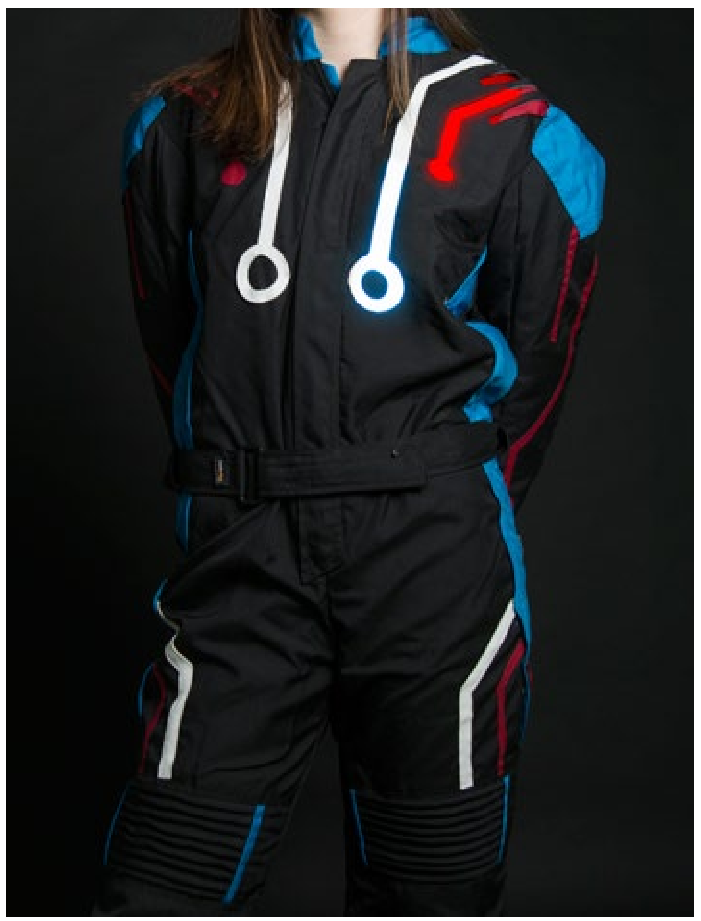
The communicative function appeared in four of them (2, 5, 6 and 7), from three different smart material typologies. The two projects that used luminescent materials correspond to this kind of function. In the four projects, the only sense involved in the dynamic experience was sight.

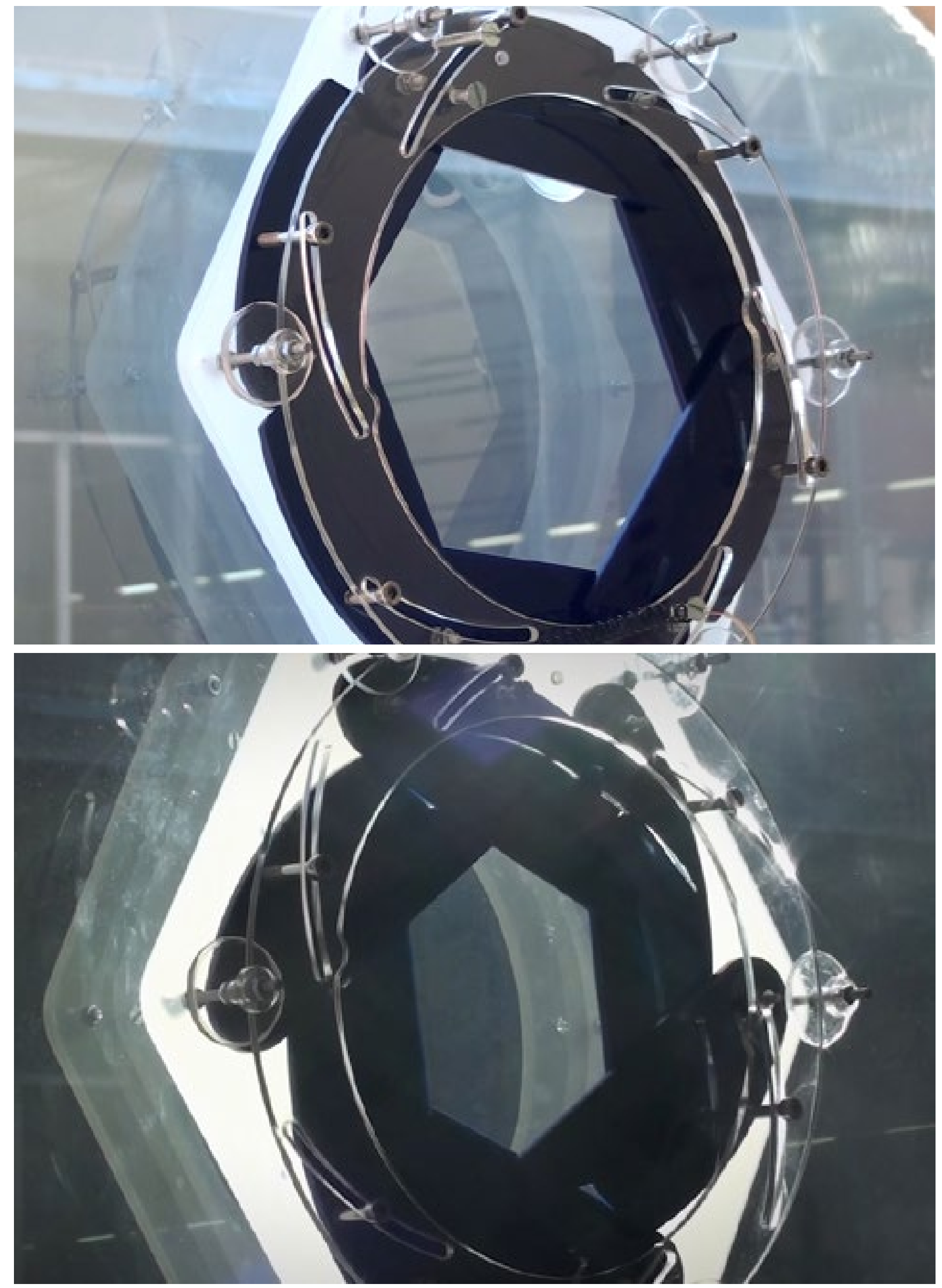
It emerged that sight is the only sense involved in the dynamic experience through chromoactive materials. As far as this typology of smart materials is concerned, the results obtained were in line with the expectations, given that the colour changed during the performance. Moreover, shape details on the surface were also present as dynamic visual features.



→ **Figure 3.** Raincoat & Lolita (1)
↑↑ **Figure 4.** COCOON (2)
↑ **Figure 5.** D2GO (3)
↓ **Figure 6.** STEP-LUX (4)

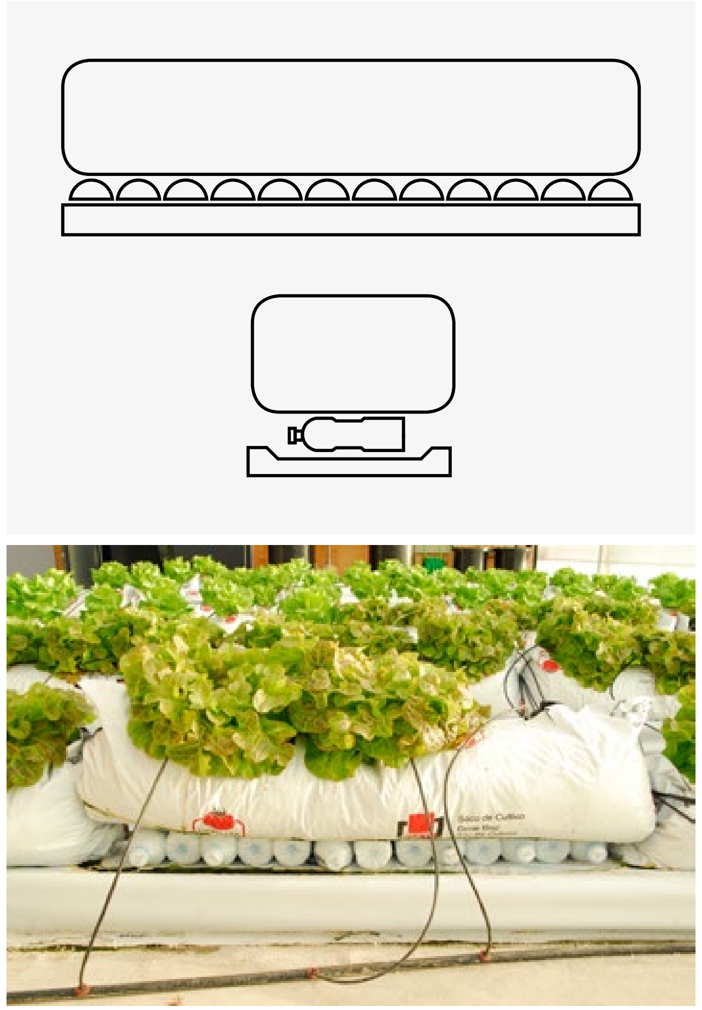






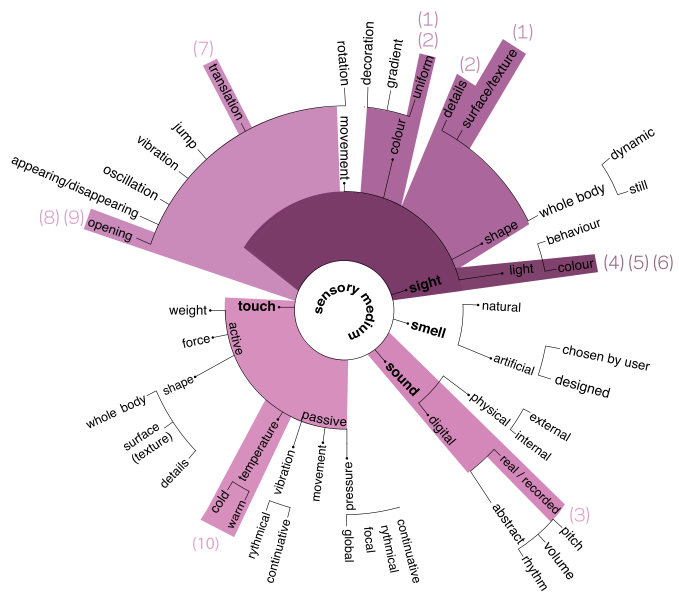
Left
↑ **Figure 7.** HEKA (5)
↙ **Figure 8.** ARMOUSS (6)
↘ **Figure 9.** SAO (7)

Right
↑ **Figure 10.** CÀLID (8)
↓ **Figure 11.** Hexafragma (9)



← **Figure 12.** PCM Soil-less crops (10) [Adapted from (Llorach-Massana et al. 2017)].

↓ **Figure 13.** Mapping of the 10 projects based on the degree of transparency used. The overlapping of more products produces a darker area on the map (violet) [Adapted from (Colombo 2016)].



	Project Title	Project number	Sensory modality	Dynamic experience functionality
Case study 1 - Chromoactive materials	Raincoat & Lolita	1	Sight → colour and shape	Expressive function
	COCOON	2	Sight → colour and shape	Communicative function
Case study 2 - Energy harvesting materials	D2GO	3	Sound → digital	Operative function
	STEP-LUX	4	Sight → light	Operative function / Consciousness
Case study 3 - Luminescent materials	HEKA	5	Sight → coloured lights	Communicative function
	ARMOUSS	6	Sight → light	Communicative function
Case study 4 - Shape memory materials	SAO	7	Sight → translation movement	Operative function / Communicative function
	CÀLID	8	Sight → translation movement	Expressive function
	Hexafragma	9	Sight → opening and closing movement	Operative function / Consciousness
Case study 5 - Phase change materials	PCM Soil-less crops	10	Touch → warm temperature	Operative function / Consciousness

Table 2. Case study classification based on the sensory modality, the dynamic experience functionality and the smart material typology.

In the energy harvesting typology, two sensory modalities, sight and sound, were used. Sight stimulus comes in the form of light, whereas sound stimulus is felt as a digitally recorded drum sound.

As expected, sight was the only sense involved in the dynamic experience through luminescent materials.

Despite the fact that shape memory alloys can be also used to create tactile experiences with pressure or temperature, sight is the only sense involved in the case studies analysed. The three examples are focused on opening-closing and translation movements.

The phase change material (PCM) releases thermal energy when turning into the solid state and generates a tactile experience.

4 CONCLUSIONS

Some considerations related to how the existing MDD method has been applied can be extracted from the comparison between case studies.

Direct experimentation, together with the introduction of the material selection at the beginning of the project, allowed students to acquire skills in designing and selecting materials, bearing in mind the technical and sensorial properties, while treating both properties synergically.

The analysis has highlighted a tendency in the use of sight to create dynamic experiences (colour, light, shape or movement). It was an expected result in the case of chromoactive and luminescent typologies. Moreover, it has presented an opportunity of differentiation. The possibility of using the sense of smell, which didn't appear in any project, could be investigated in future studies due to its strong emotive impact and its great influence on our behaviour.

The students met some difficulties in considering senses other than sight. The low diversity in the sensory mediums stimulated in the case studies showed that the sensory map, apart from being used as an analysis tool, could be used as a design tool to support designers to explore dynamic products and to encourage them to design for the other senses.

The application of the methodology could be improved by the combination of the sensory map as a design tool together with the visual table of commercial smart materials. This combination could be helpful in exploring uncommon sensory mediums and designing engaging dynamic sensory interactions through smart materials.

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