# EXPLORING THE IMMATERIAL

The sincerity and the ambiguity of chromogenic materials useful for designing a surprising User Experience


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I would like to spend some words before
the beginning, to thank my supervisors
Professor Barbara Del Curto and
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during these months to better center
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to valorise this special and interesting
topic focused on smart materials and
chromogenic materials.
I am feeling very happy for having
had the opportunity to write my thesis
both in Milan and Saint-Etienne (FR),
meeting new people and different work
environments.
In conclusion, I dedicate my thesis to my
parents, Dario and Monica, who helped
me during this University journey and to
Fulvio, who always supports me with his
good mood and his precious advices.

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# Abstract

The main purpose of this thesis is to analyse the chromogenic materials – also called colour-changing materials – construing several case studies, to suggest in conclusion possible design guidelines to make the use of chromogenic materials easier in following design projects and reseraches. The case studies analysed were bibliographical and physical ones. They have been researched in books, from examples already explored by students and directly from physical tests during the internship in the laboratory at the Ecole des Mines de Saint-Etienne.
The thesis is characterised by different investigation levels, all related to each other. The first questions this thesis aims to answer refer to colour-changing materials connected to meaning of colours and their possible transformation from one to another, especially related to cold and warm aesthetic sensations. A questionnaire related to thermochromic samples previously prepared was used to get real and physical answers. The introduction topic refers mainly to the reciprocal influence between sight and touch. Starting from this point, the relations between chromatic field and temperature, and between warm / cold colours on visual level and colour-shift materials are introduced because they lead to the central point of the thesis.
The second main point of the thesis is related to colour shift rapidity that is strictly linked to surprise effect and feedback of proper and correct usability. For responding these points of the thesis, the personal inputs

used were several questionnaires with five thermochromic cylindrical samples to test colour-changing materials perceptions and evaluating the warm and cold sensations of the starting and final colours of each sample. The main questions that refer to this topic are linked to colour-shift rapidity and surprise effect relation, UX feedbacks using colour-changing materials, colour-changing materials and faster cognitive outcomes.

The final point of the thesis consists in summing up the extra values that chromogenic materials may create during the usability experience to trigger emotions and surprise during design products usability. The conclusive results lead to the creations of final guidelines that designers could use during their projects with chromogenic materials to emphasize the surprise effect that is directly embedded in these materials.

# Abstract

L'obiettivo principale di questa tesi è quello di tratteggiare delle linee guida che indirizzino e aiutino i designer nella scelta dei materiali cromogenici per creare un design di sopresa. L'attenzione è rivolta soprattutto ai materiali cromogenici, che presentano delle interessanti proprietà visive. La ricerca si sviluppa a partire dall'analisi di tali materiali smart, che cambiano reversibilmente o irreversibilmente colore (output) a seconda di determinati stimoli esterni (input). Le linee guida, che risultano alla fine della tesi, sono supportate da alcuni casi studio che possano meglio descrivere un corretto uso dei materiali cromogenici - specialmente termocromici e idrocromici - nel contesto più ampio e vario della user experience. I casi studio analizzati sono tratti dalla bibliografia di tesi e da campioni fisici realizzati durante un periodo di studio all'estero focalizzato su un'attività di tirocinio laboratoriale presso l'Ecole des Mines de Saint-Etienne, nel Dipartimento di Ricerca e Materiali.
La tesi è strutturata secondo diversi livelli di ricerca, tutti interconessi fra di loro. La prima domanda dalla quale la tesi prende piede riguarda il significato dei colori e la loro trasformazione cromatica nel tempo - quest'ultima rappresenta la principale proprietà dei materiali cromogenici - focalizzando l'attenzione soprattutto su colori che possano comunicare sensazioni di caldo o freddo. Per questo motivo, la realizzazione di un questionario è risultata necessaria al fine di avere

determinati valori da un punto di vista qualitativo e quantitativo.
Il tema introduttivo si riferisce principalmente all'influenza reciproca fra vista e tatto e l'analisi del rapporto fra la sfera cromatica - visiva e quella tattile di temperatura.
Il secondo punto di tesi riguarda la rapidità del cambiamento di colore, strettamente legata al tema dell'emozione di sorpresa, che costituisce il fulcro di tutto la discussione. Essa può infatti essere controllata per ottenere una risposta immediata e quindi un feedback positivo da parte dell'utente, o al contrario essa può causare una reazione negativa da parte dell'utente finale, in seguito ad un'assenza - totale o parziale - di trasformazione di colore, che può provocare frustrazione, non garantendo una corretta user experience. La rapidità del cambiamento di colore del materiale può inoltre essere un utile strumento per identificare un corretto o scorretto utilizzo del prodotto.
Infine, vengono ipotizzate delle strategie di design a partire dalle principali conclusioni derivate dall'esperimento svolto con i materiali termocromici unendo inoltre svariati spunti bibliografici. Gli strumenti pratici - serviti per delineare alcune interessanti conclusioni, fondamentali per descrivere le linee guida progettuali finali - sono stati la realizzazione di cinque campioni di materiale termocromico, grazie ai quali si sono potute analizzare le sensazioni di caldo e freddo legate alla dimensione visiva del colore ed anche la reazione di sorpresa in seguito all'esperienza tattile da parte dei testers e all'immersione dei campioni in acqua a temperature elevate e un questionario a domande aperte e chiuse relative all'esperienza con tali campioni.
Successivi scenari di impiego dei cromogenici infine potrebbero essere rappresentati dall'utilizzo delle particolari proprietà fisiche dei materiali cromogenici, su prodotti che aumentino la comprensione delle funzionalità del prodotto, il suo utilizzo - corretto o scorretto - e la possibilità di veicolre emozioni come la sorpresa in contesti interattivi di apprendimento.

0

# INTRO

# 0. Introduction

In the last few years new scientific discoveries have been made in smart materials field that is becoming more and more relevant in the scientific panorama for design-driven innovation. This thesis focuses particularly on the immaterial sphere that surrounds the design product characterized by human sensations. "Immaterial(s)" is thought here as extra value that colour-changing materials add to the design product, due to user's personal feelings related to colours, due to the personal and cultural background that affects human beings' perceptions of design objects. The perceptions are physical but extremely connected to an invisible world characterized by psychological, subjective, personal human aspects constituted by human emotions. Moreover, colours are properties that have to do with an immaterial thing like light, that cannot be touched and that changes the way human-beings percept a specific design product. **It is interesting to analyse the way colour-changing materials modify our perceptions of design products. In fact, objects and their material environments change with smart materials, while the mode, in which they are conceptualised, experimented with, designed, and manufactured, also change.**[1]
The world of colour-changing materials is analysed here, relating it to the "immaterial" human surprise – that is the only emotions I wanted to investigate in this paper - and the aim is mainly the one to propose several guidelines for employing chromogenic materials in design field. A great importance is addressed to chromogenic materials because they have an additional power and, instead of common materials, they can change their physical properties under the control of human eye. Then, they can be considered as "alive" matter and for this

1 Ferrara M., & Bengisu M., (2014). Intelligent design with chromogenic materials. Journal of the International Colour Association, 13 (3), p.p. 54-66, Retrieved from https://www.researchgate.net/publication/269296104_Intelligent_design_with_chromogenic_materials

reason the main core of the thesis is exploring the human reactions by using them in recent design applications possibly focusing on integrating intelligence, autonomy and especially multi-functionality. Chromogenic materials potentially permit the realisation of products with similar functional abilities while saving energy with respect to traditional systems. [2]. But the important investigation to be conducted is the possibility to use chromogenic materials to give certain feedbacks to direct user's product usability in a proper way, evidencing the correct or incorrect use of the product, especially if the user is a neophyte. The colours have a great weight in design field because they are perceived as skin of products and when the product designer chooses a colour, he chooses indeed a meaning for the object he decided to realize[3]. The products colours are the first things that the user will visually feel, and they cover a significative role in users' market choice. Chromogenic materials also are useful instruments for elevating the expressive value of objects and environments[4] and they create a more complex significance in design products. Colours can be used to convey emotive content as well as assist with the look and feel of the design product, evoking passions and feelings in the users.
The thesis tries to underline a difference between diverse users' surprise responses and feedbacks – after touching and using thermochromic materials samples. Another purpose was concerned with the verification of users' visual and tactile perceptions of design products. It is based on their specific shift of colour, from colder to warmer ones to evaluate a "temperature aesthetics" and the shifts of the samples. One of the most interesting points I asked myself consists in the assessment of colour-changing materials for capturing visive attraction, to improve users' cognitive and personal outcomes.

2 Ferrara M., & Bengisu M., (2014). Intelligent design with chromogenic materials. Journal of the International Colour Association, 13 (3), p.p. 54-66, Retrieved from https://www.researchgate.net/publication/269296104_Intelligent_design_with_chromogenic_materials

3 Fleming R. W. (2013), Visual perception of materials and their properties, Vision Research, 94 (3), p.p. 62-75DOI: 10.1016/j.visres.2013.11.004
Falcinelli R., (2017), Cromorama: come il colore ha cambiato il nostro sguardo. Einaudi

4 Ferrara M., & Bengisu M., (2014). Intelligent design with chromogenic materials. Journal of the International Colour Association, 13 (3), p.p. 54-66, Retrieved from https://www.researchgate.net/publication/269296104_Intelligent_design_with_chromogenic_materials

# 1

# SMART MATERIALS

# 1. Smart materials

## 1.1 Smart materials definition

Smart materials have been under immense investigation in all fields of science and in all corners of the world over the past decades. **Smart materials consist of materials which respond to changes in their environment, thus rendering them stimuli-responsive.** [5] Smart materials can be described as interactive matter/substance that can be controlled using specific stimuli – physical inputs – to obtain certain resulting physical properties – outputs. The inputs and outputs are related to temperature, light, humidity, electric field, magnetic field, etc.


*Fig. 1: Basic functioning of smart materials. Source: Smart materials, development of new sensory experiences through stimuli responsive materials*

Smart materials are adaptive materials that modify their properties adjusting themselves to the specific situation in which they are used, and they react with an output to physical and chemical stimuli in a repeatable and reversible ways. Smart materials are characterized by specific peculiarities like the following ones:

o immediate response (immediacy) to the stimuli: the transition phenomenon occurs as soon as the material receives the input and reverse when the input stops;

5 Bearat, H.H., (2011), *Injectable Biomaterials, Environmentally responsive injectable materials.* Edited by Brent Vernon.

o **They have different properties depending on these various environmental states (transiency)[6]** . The material has different possible states and change between one another;
o The special physical properties of smart materials are intrinsic values of the materials and they are not due to outer operations on them (self-actuation). The behaviour is internal of the material: the material act both as sensor and actuator;
o The response of the material is local, and the output is produced at the point the input was given (directness). The response of the material occurs where and only where the input is applied;
o **A single environmental state can only lead to a unique and constant and repeatable response of the smart material (selectivity).** [7] The transition occurring in the material is predictable and repeatable.

There are also two important physical characteristics related to smart materials: the activation time - that is the time needed for the effect to occur from the moment the input is received - and the relaxation time that is the time needed for the material to turn back to its initial state.
There are many different types of smart materials that can be divided in large number of categories with their own specific physical properties. These materials categories are very diverse from each other and include lots of various physical aspects. For this reason, in this first paragraph a general and summary idea of smart materials is proposed with a brief description of the main classes of smart materials. They are not going to be discussed in detail because this is not the principal aim of the thesis and it can result as an extremely wide topic to deal with. Moreover, it is not significant to the purpose of the thesis subject that is related to the chromogenic materials sphere that is going to be explained in a more exhaustive modality.

6 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

7 Addington, D.M., & Schodek, D. (2005). Smart materials and technologies for the architecture and design professions. Amsterdam [etc.]: Elsevier Oxford Architectural press.

## 1.2 Classification - inputs and outputs

Smart materials can be classified in diverse ways. Referring to the bibliographical literature by Addington and Shodeck (2005) the first classification modality is referred to smart materials type 1 and type 2, that are respectively referred to **intrinsic response variation of material to specific internal/ external stimuli and materials in which the responses can be computationally controlled or enhanced**.[8] Type 1 materials are thermochromic, magnetorheological, thermocropic, shape memory materials. Type 2 are photovoltaic, thermoelectric, piezoelectric, photoluminescent, electrostrictive materials.

The main smart materials properties, referring to the Type 2 category, are immediacy, transiency, self-actuation and directness (and selectivity). A smart materials sorting can be done using the application of the previous five properties and it can be the following one:

- Property change capability
- Energy change capability
- Discrete size location
- Reversibility

The existing classification of smart materials that refers to D. Michelle Addington and Daniel L. Shodeck's book "Smart materials and technologies for the architecture and design profession" is represented in the image list in the following page (Tab.1). It represents a materials scheme based on the inputs and outputs subdivision. Each relation between inputs and outputs corresponds to a specific type of material.

8 Addington, D.M., & Schodek, D. (2005). Smart materials and technologies for the architecture and design professions. Amsterdam [etc.]: Elsevier Oxford Architectural press.

| Type | Input | | Output |
|---|---|---|---|
| Type 1: PROPERTY - CHANGING | | | |
| Thermochromic | Temperature difference | → | Colour - change |
| Photochromic | Radiation (light) | → | Colour - change |
| Mechanochromic | Deformation | → | Colour - change |
| Chemochromic | Chemical concentration | → | Colour - change |
| Electrochromic | Electric potential | → | Colour - change |
| Liquid Crystal | Electric potential | → | Colour - change |
| Suspended particles | Electric potential | → | Colour - change |
| Electrorheological | Electric potential | → | Stiffness / Viscosity change |
| Magnetorheological | Electric potential | → | Stiffness / Viscosity change |
| Type 2: ENERGY - EXCHANGING | | | |
| Electroluminescent | Electricity | → | Light |
| Photoluminescent | Radiation (light) | → | Light |
| Chemoluminescent | Chemical concentration | → | Light |
| Thermoluminescent | Temperature difference | → | Light |
| Light-emitting diods | Electricity | → | Light |
| Photovoltaic | Radiation (light) | → | Electricity |
| Type 2: ENERGY - EXCHANGING (reversible) | | | |
| Piezoelectric | Deformation | ↔ | Electricity |
| Pyroelectric | Temperature difference | ↔ | Electricity |
| Thermoelectric | Temperature difference | ↔ | Electricity |
| Electrostrictive | Electricity | ↔ | Deformation |
| Magnetostrictive | Magnetic field | ↔ | Deformation |

***Tab.1***: *Smart materials classification: Addington and Shodek, 2005*

This can be a valid way to classify smart materials but another and more recent modality exists. Remembering that smart materials classification is important to better understand the range of potential uses, the other possible and more recent way to sort these materials is to **separate them by input and output, which represents their main functionality, in terms of materials selection criteria**.[9] In fact, **expressing the functionality of smart materials is more relevant to design activity than conventional classifications by materials families and properties**. [10] To better understand this concept, two reference graphs are shown (fig. 2 and fig. 3), which link the input, on the left side, with the output on the right side for each type of functional materials. The different types of materials are represented by a link between the input and output associated to them. For example, photochromic materials are represented by the link between the input 'Light' and the output 'Colour'. The graph can be useful to explore the possibilities offered by smart materials: as they show numerous different behaviours, it can be difficult to envision all the possibilities offered by these materials, and such a map can provide first guidelines. One can look at the materials that correspond at a given input he wants to use to switch on the object or add an additional functionality, or he can see which materials are able to produce the desired response, and which type of input they need to be activated. Finally, one can simply use the map to get basic information about what kinds of smart materials exist, as a source of inspiration. Such a graph could also be used to know which classes of smart materials can be adapted for an application in a given project. **Another way to use such a graph is to pick up the most appropriated type of material given the interaction one wants the object to have with the user. For example, if a designer wants an object to react to surrounding temperature by changing shape, a possible way is to use Shape Memory Materials (SMM). Several**

9 Ashby, M., Bréchet, Y., Cebon, D., & Salvo, L. (2002) Selection Strategies for Materials and Processes. Materials and Design, 25 (1), p.p. 51–67, Retrieved from https://doi.org/10.1016/S0261-3069(03)00159-6

10 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

**options are available to achieve this effect, and practical constrains such as, e.g.: shape, size, required production rate, etc will decide on the final choice (e.g.: Ni-Ti shape memory alloys).** [11] Additionally, some of these materials exhibit a bi-directional response: they can react to an input creating an output, but also react to the former output and having effect on the input. For instance, **piezoelectric materials respond to an electric potential by generating a deformation and respond to a deformation by producing an electric tension. Therefore, these bidirectional smart materials can be used in a different way than the other ones, whose response is mono-directional.** [12] If we focus on making the sensory properties of an object variable and interactive, several classes of materials become more interesting than others. It is especially the case for colour changing, light-emitting and shape changing materials, which variations affect directly the perceptions of the user.

Another way to describe the input and output classification of smart materials is represented by the fig.3, in which the initial stimuli and the consequent response are associated. As in fig. 2 from the same stimuli, diverse outputs can derive. An innumerable number of smart material type exist nowadays. The summary scheme that is represented here is based on transition phenomena and allow the reader to better visualise smart materials differences and potentialities. **Transition phenomena are symbolized by the coloured lines that connect inputs and outputs together. The colour in which the transition phenomenon is registered, always corresponds to the colour of the input.** [13]

11 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

12 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

13 Lima L.M. (A.A. 2016 / 2018), Material Information. Une étude des matériaux intelligents chromogènes appliquée aux systèmes d'information ambiants. Ecole des Mines de Sait Etienne. Saint-Etienne.

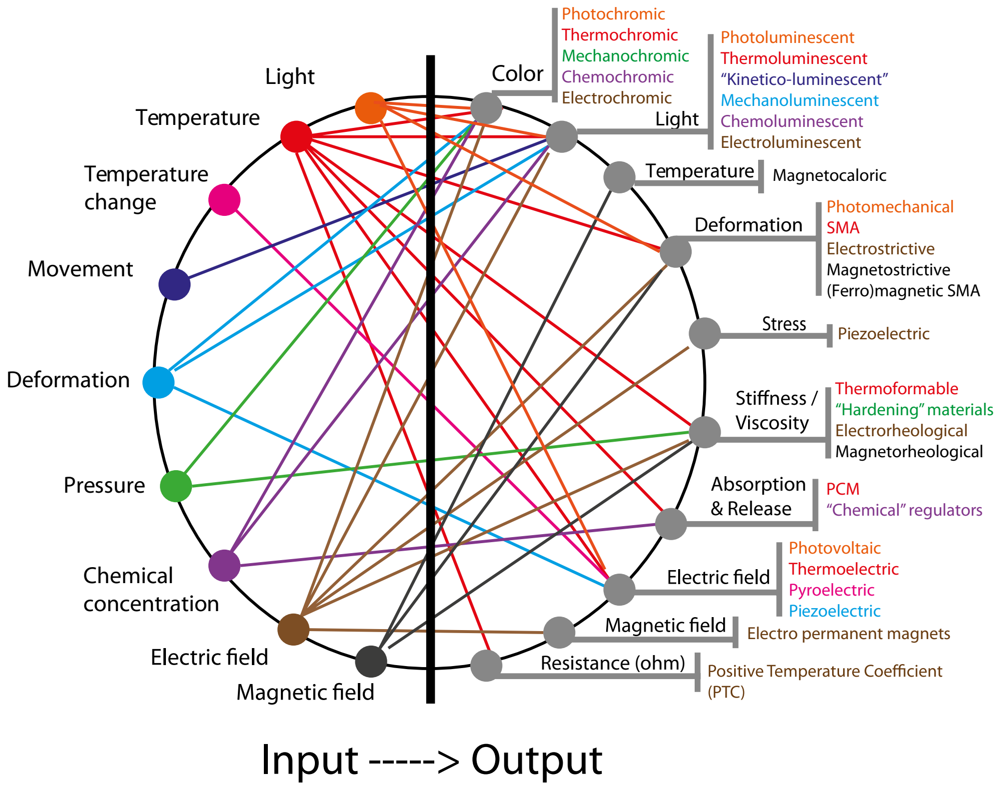



*Fig. 2: Second classification of smart materials suggested in the paper "A matter of design" Source: Esther Lefevre*

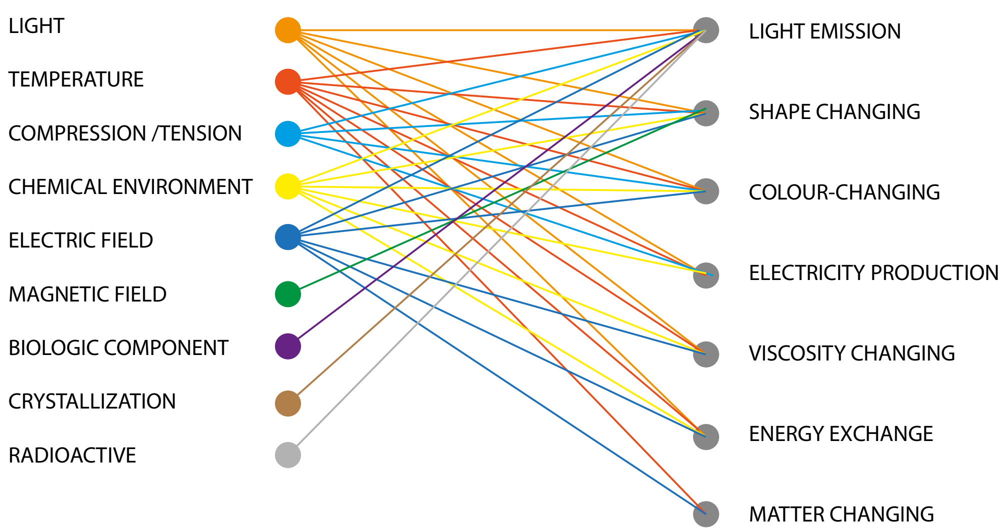



*Fig. 3 Transition phenomena depending on stimuli and response. Source: Ritter, Axel: Smart materials in architecture, Interior architecture and design, 2007 Lefevbre, Esther et al. Smart materials: development of new sensory experiences through stimuli responsive materials, 2014*

# 2

# CHROMOGENIC MATERALS

# 2. Chromogenic materials

## 2.1 Chromogenic materials from designers' point of view

The chromogenic materials can be used for many applications in different and various design fields (e.g. fashion one shown in fig.4) with the aim to create a more interactive material experience between the product and the user. The "**materials experience**"[14] refers to the experiences that people have with, and through, the material of a product. **This is a concern not only for aesthetics experiences provided by materials, but also for meaning that materials may evoke, and emotional responses that may originate from materials**.[15] It became apparent that we should look to the experience not only of end users of materials - through products - but also to the experience of designers who have the initial interactions with those materials. **This dual attention reflects the classic demarcation between attending to the outcomes of design - as particular material experiences - as well as the process of design**.[16]

**It is often very difficult to separate the meaning of the material from the meaning of the product in which the material is embedded.**[17] The meaning of the material, in this case of colour-changing materials, is related to emotional field. In this thesis the analysis will focus firstly on the meaning of colour-changing materials and on colours they can assume to communicate a (predicted) special emotion – surprise - to the final user of the product.

Colour-changing materials represent a recent working development sphere because their physical properties are alive,

14 Rognoli V., Karana, E., & Pedgley O. (2014). Materials experience fundamentals of materials and design. Amsterdam [etc.]: Elsevier.

15 Desmet P. M. A., & Hekkert P., (2007). Framework of product experience, International Journal of Design, 1(1), p.p. 57-66, Retrieved from https://diopd.org/wp-content/uploads/2012/02/frameworkproductex.pdf

16 Rognoli V., Karana, E., & Pedgley O. (2014). Materials experience fundamentals of materials and design. Amsterdam [etc.]: Elsevier.

17 Rognoli V., Karana, E., & Pedgley O. (2014). Materials experience fundamentals of materials and design. Amsterdam [etc.]: Elsevier.

and they change under the control of human eye, after applying previously prepared inputs (fig 4 and 5). They communicate something in real time thanks to their transformation of colour. Hence, designers can use them to create interactive design products that have more valuable characteristics.
It is not easy for a designer to measure himself with colour field – the relationship with colour is largely infra-symbolic and is closer to our relationship with food than to our relationship with forms. Colours allow no rational justifications or logical explanations (apart from the cases where there is a functional motivation). The only possibility lies in developing a strategy based on a phenomenological reading of reality (that is, of the trends of collective choices) and of its developing behaviour. Recognizing trends and interacting with them is the only attitude a designer can have with respect to the colour variable that is not purely intuitive.
But how much control do designers have over these apparently intangible emotional human responses? Can we indeed design for special emotions experiences, like the one of surprise for instance? And in the field of human factors, this approach is restricted to a generalised attempt to make products pleasurable or enjoyable.
**For emotion-driven design to become a mature design strategy, we need to understand why, when, and how products**

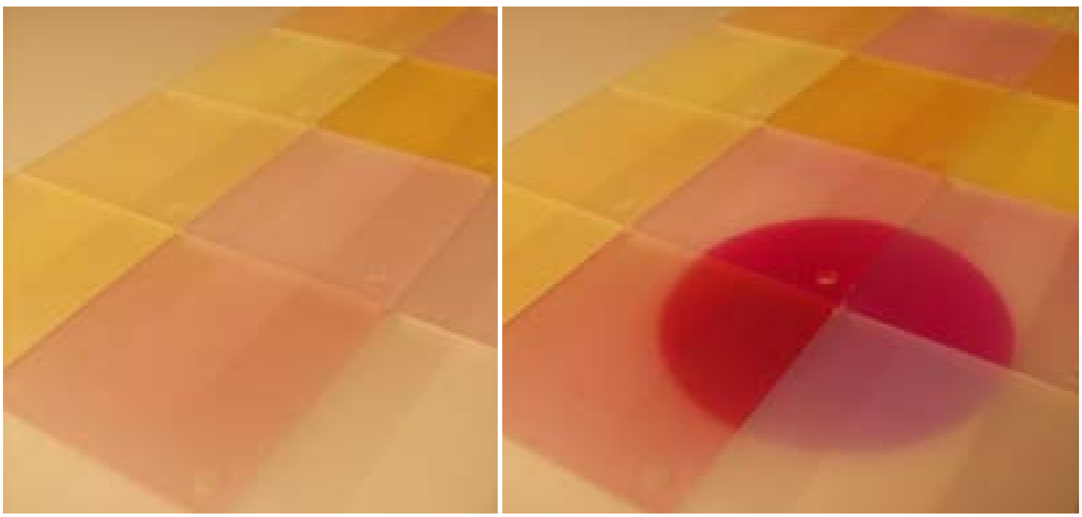


***Fig.4, Fig 5:*** *Reversacol photochromic dye before and after the colour-change due to UV light. Source: Material District https://materialdistrict.com/material/photochromic-pigments/*

**evoke the emotion of surprise.**[18] This topic is strictly related to design marketing and product experience. Moreover, it represents an important design value to analyse and think about while designing a product, to predict good users' response and feedbacks.
This thesis does not focus on emotional aspects – except for the sense of surprise that the product can create in the utilizer during the use – because it is a complex world to analyse, especially if we refer to the perceptions sphere. These two experiences – the emotional and the perceptions ones – are very diverse from each other and an analysis on both would have created confusion, without focusing on the important point that represents the real matter of the thesis. According to the final objectives of this thesis, the analysis of the wide range of human emotions that can be linked to the product experience, is not so useful here because smart materials – and especially chromogenic materials – drive and trigger the special sense of surprise, and due to this fact it attires the main part of the attention in this discussion.

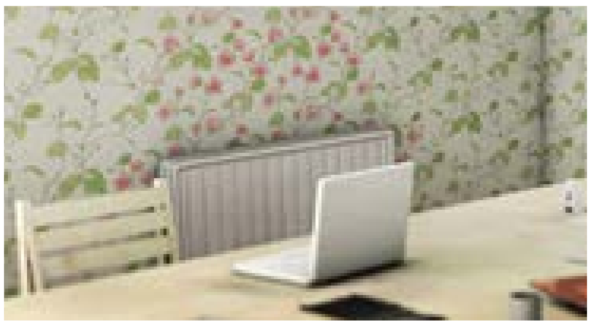



***Fig.6 and Fig 7****: Thermochromic wallpaper by Shi Yuan*

18 Desmet P., Hekkert P. & Hillen M. (2003), Values and Emotions; an empirical investigation in the relationship between emotional responses to products and human values, Applied research, practice based research: case studies, Delft University of Technology, School of Industrial Design, The Netherlands, Retrieved from https://www.researchgate.net/publication/238659590_Values_and_Emotions_an_empirical_investigation_in_the_relationship_between_emotional_responses_to_products_and_human_values

## 2.2 Chromogenic materials definition

Materials that change colour are scientifically termed chromogenics and they are described as "chameleonic" because they change their colour reversibly as a response to changes in environmental
condition (such as change of temperature, brightness, etc.) or by induced stimuli. [19] The phenomena which these materials are based on is called chromism that consists of a change in the microstructure or electronic state of the substance. To better understand this topic, it is necessary referring to the natural laws that express the theory of colours. In fact, the visible light that appears to us as white light is formed by various colours. [20] My analysis in this thesis refers especially on colour-changing materials but a hint about light-emitting materials is obliged because they also refer to lighting response as outputs. Colour-changing and light-emitting materials have a direct effect on the visual appearance of an object and present a large variety of possible inputs – as it can be visualized in fig.2 and fig.3 - therefore they can be used in a wide variety of applications. For both colour-changing and light emitting materials, possible inputs are light (photochromic, photoluminescent), change in temperature (thermochromic and thermoluminescent), deformation or pressure (mechanochromic and mechanoluminescent), chemical concentration (chemochromic and chemoluminescent) and electric field (electrochromic, electroluminescent and LEDs). Some materials also change colour when they are submitted to a pressure change. 21

19 Ferrara M., & Bengisu M., (2014). Intelligent design with chromogenic materials. Journal of the International Colour Association, 13 (3), p.p. 54-66, Retrieved from https://www.researchgate.net/publication/269296104_Intelligent_design_with_chromogenic_materials

20 Ferrara M., & Bengisu M., (2014). Intelligent design with chromogenic materials. Journal of the International Colour Association, 13 (3), p.p. 54-66, Retrieved from https://www.researchgate.net/publication/269296104_Intelligent_design_with_chromogenic_materials

21 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

### 2.2.1 Light-emitting materials

The use of phosphorescent pigments is now new, but their communicative potential is far from used up. Their ability to mark the darkness with the memory of a light that is no longer present confers a special life to the surface of objects, linking that surface with the history of its surroundings. **A new sensibility has been generated with respect to these objects, which do not undergo events statically, but bear the mark of each event on their surface.** [22] In the 90s Manzini said that and today a lot of new applications are created in design field, but innovative usages can always be design. Phosphorescent surfaces are the forerunners of the family of reactive surfaces (which relate to the ambient) and expressive surfaces (which communicate their state and the changes that have occurred in it). **Other reactive surfaces can be easily imagined, even using quite simple technology – soft surfaces that preserve for a certain time the shape of whoever touched or used them; surfaces made to be used up, leaving a trace of the use that was made of them.** [23]
Some of the most interesting case studies I selected from the bibliography are the ones shown in these pages. They refer to photoluminescent materials that glow in the dark and that can be used for very diverse uses (as surfaces coatings or as part of the products material, interior design, fashion clothing, etc). I selected them to create a general idea of the topic and of their application in everyday uses.

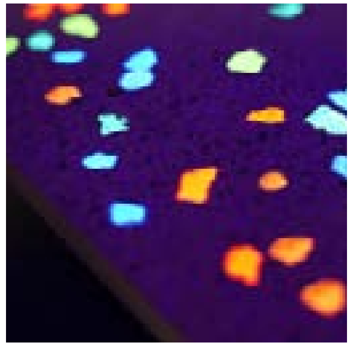
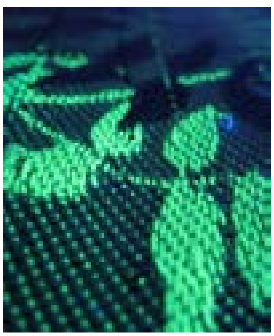
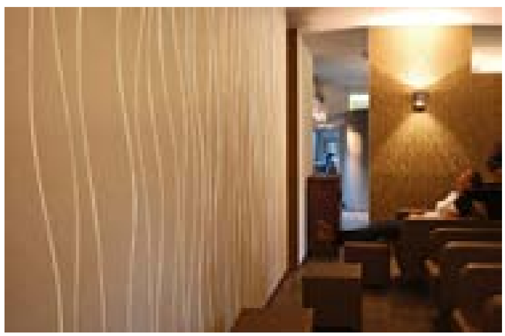


*Fig.8, Fig 9 (up): Luminous concrete. Source: Material District https://materialdistrict.com/material/luminous-concrete/*
*Fig.10 (down from left side): Photoluminescent Mosaic. Source: Luce Dentro http://www.lucedentro.com/en/products/spaswellness/mosaic/*
*Fig 11: Woven Light Textiles. Source: Material District https://materialdistrict.com/material/woven-light-textiles/*
*Fig 12: Light Paper.*





22 Manzini E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.
23 Manzini E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.

### 2.2.2 Change of colour

Some existing products and concepts made of chromogenic materials are described in this paragraph, and they particularly refer to the cousine field and they represents especially thermochromic tools used for cooking that change their colour due to high temperature levels (fig. 13, fig. 14 and fig.15, fig. 16). The last example represents an exterior design product to underline how living the colour-change of materials is possible in many different ways in a public context of usability.

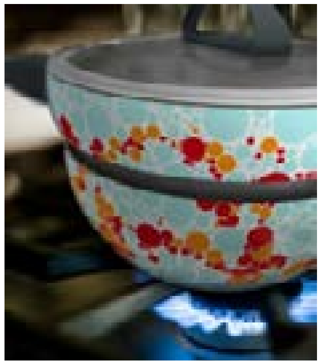


***Fig.13, Fig 14****: Coral Pan by W. Spiga and J. Martins. Source: https://www.behance.net/gallery/339941/Coral-Pan*

***Fig.15, Fig 16****: One by Vessel Ideation by Grace Bonney. Source: https://www.design-sponge.com/2009/04/one-by-vessel-ideation.html*

***Fig.17, Fig 18****:Thermochromic Color Changing Bench By Artist: Sam Falls, New York. Source: https://www.movingcolor.net/*

## 2.3 Classifications, mechanism of colour-shift through existing chromogenic applications and case studies

The list of materials shown in fig.2 previously described[24] represents the diverse typologies of chromogenic materials that go with the type of correspondent stimulus (input) that is necessary to modify the material physical characteristic. Although it is important to know what kinds of smart materials exist to understand the possibilities that smart materials offer, it might not be totally enough to know how to use them. It can be useful to know why and how the material exhibits its special behaviour. Another way to envision the possibilities is to look at already existing applications. The diverse types of chromogenic materials will be linked to specific case studies to explain better their functionalities and physical characteristics. The cases studies refer to everyday life fields, with a special focus on sports field and children field, just to name a few, because the thesis approaches especially new potential application subjects. Colour is a fundamental property of light, in fact a focus on light and its interaction with matter is very important to define photoluminescent and chromogenic materials. Light is characterized by different orientations that create diverse and special lighting effects on the surface of the materials. In fact, light can be delayed, redirected, absorbed or converted due to the orientation of light rays and the surfaces of the materials which light is oriented to. The molecular structure of the material is another important factor to describe the light-matter interactions. The various chromogenic materials are described also through existing products, that are mostly available on the market. The reader will have a better panorama of chromogenic materials and their possible applications nowadays. To allow the reader to visualize better and globally all the examples chosen, a table wascreated to arrange them[25], comparing the common material objects to the chromogenic ones (chosen between the various case studies quoted in the next paragraphs).

24 See figure 2 and fig.3 on page 24
25 See table 2 on page 44 and 45

### 2.3.1 Photochromics

*Fig.19: Sun Activated photochromic pigment trial pack. Source: https://www.sfxc.co.uk/products/sun-activated-photochromic-pigment-trial-pack*

Photochromic materials respond to a variation of incoming light intensity or the spectram distribution of light modifying their colour reversibly. They are transparent and colorless when the light is soft and they don't absorb light. When the bright stimulus is removed, the colour disappears because the material returns to its original molecular configuration[26] (as the photochromic lens of the sunglasses in fig.20). This property is due to the special molecular structure of the material and it is based on the principle of reversible chromatic change of some chemical substances that are between two layers of different energetic absorptions when they are exposed to a lighting flow. They are materials that are capable of absorbing energy and of modifying the outgoing chromatic spectrum with electromagnetic radiations. The photochromic devices have interesting uses in situations in which the limit of the radiations is the main aim to reach. Photochromic materials are in pigments (fig.19), glasses (fig.20 and fig.21) and polymers (fig.22). One of the most known applications is the one related to lenses that cover automatically the sunlight and they are on the market since 20 years (fig.20). The photochromic materials are part of the metal, ceramic and polymer families of materials and they can be processed in bulk and surface using them as pigments, ink or thin films. The colour intensity depends on the input intensity and duration.

***From the left side to the right one:***

*Fig 20: Sensity Photochromic Lenses. Source: MiVision https://www.mivision.com.au/2017/08/prescription-sunglasses-and-photochromics-your-value-add-niche/*
*Fig 21: Photochromic glazing by Sage Glass (Saint Gobain, FR). Source: John Desmond Limited https://www.johndesmond.com/blog/products/glass-overview-chapter-3-a-simple-question-a-city-without-glass/*
*Fig. 22: Bracelet indicateur de rayons UV. Source: ebay*

26 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. p. 13; Cham: Springer.

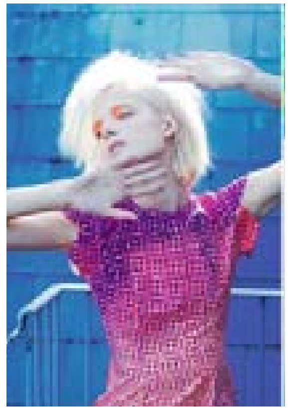
Regarding the photochromic textiles (as in fig. 23, fig.24 and fig.25 in which various photochromic dresses are presented) and photochromics dyes, some general laws are written to know what to expect from the materials. **Ideally, any organic photochromic system should be of following qualities:**

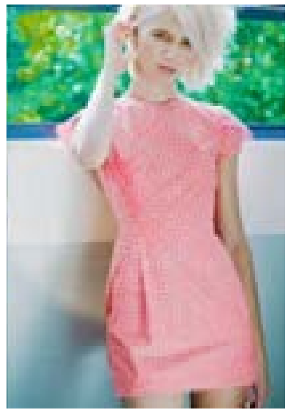
**• Development of colour in photochromic systems – in order of being classified a sensor, the dynamics of colour development must be a rapid reaction to source of UV light;**

**• Return to the rest state (colourless) – the rate of fading of the system must be controllable and all possible influences, such as influence of heat or sunlight, investigated;**

**• Wide palette of colours – range of the colours being exhibited as result of irradiation by UV light should be across the visible range of light;**

**• Rest state in which colour is not exhibited – the state in which there is no excitement of the electrons, caused by external stimula should be as colourless as possible Photochromic dye appropriately applied onto textile material forms a photochromic system, which in case of fulfilling the abovementioned demand is in fact a sensor. Sensor capable of reacting to UV light of exactly defined spectra and intensity in a pre-programmed, controllable manner. Described as such, system alerts and protects the wearer against negative influence of UV irradiation and classifies the very definition of a "smart textile". Having fulfilled all these demands, investigations should be made to find out whether any derived qualities have arisen as result of applying photochromic molecules onto textile fibres. These qualities could be certain antibacterial or antifungal properties added onto textile materials.** [27]





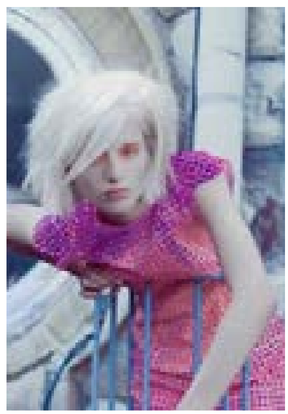


***Fig. 23, fig.24 and fig. 25 (from the upper one to the lower one):*** *Orange petal dress that is made of stretch-cotton hand-screen printed. Photochromic screen-print changes from clear to purple sunlight. Metallic gold back-zip and pink satin trim. Courtesy of Amy Winters*

27 Durasevic V., Osterman D. P., & Sutlovic A. (2011), From Murex Purpura to Sensory Photochromic Textiles, Textile Dyeing, IntechOpen, 12 (5) p.p. 61 – 62, DOI: 10.5772/21335

***On the rght side from the upper to the lower images:***
***Fig. 26:*** *Colour-changing mugs: Source: ebay*
***Fig. 27****: Warm touch activated products. Source: https://www.youtube.com/watch?v=SZ78qNpq3mA*

***The image on the right:***
***Fig. 28:*** *Thermochromic table 'Linger A Little Longer' by Jay Watson design. Source: www.jaywatsondesign.com/*

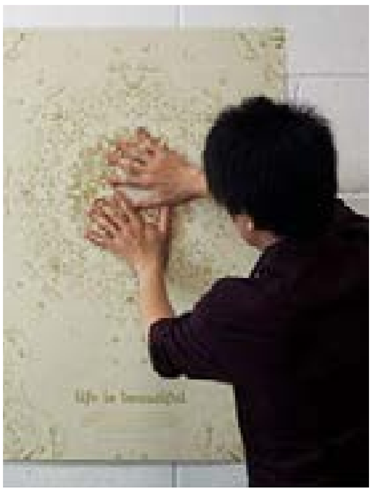
### 2.3.2 Thermochromics

According to Mott's definition (1974) **"the thermochromic effect occurs over a range of temperatures, which is observed as a gradual colour change, i.e. continuous thermochromism. Discontinuous thermochromism involves a structural phase change at the transition temperature. This phase change can be first- or second-order in nature, and may be reversible or irreversible, as governed by the thermodynamics of the system"**. [28]
The activation temperature is between -10° C and 120° C. The activation time could be very rapid. They are from metallic, polymeric and hybrids materials families. The reversible chromatic variation happens because of chemical reactions or due to variations of temperature. The thermochromic change can occur with several organic and inorganic substances, films of metallic oxides that can transform themselves in conductors at specific temperatures. The organic thermochromic compounds are divided in liquid crystals and leuco-dyes. In both cases they are encapsulated to make their use possible.

The thermochromic materials allow the end users to change the look of their room in a very special way, as in figure 29, 30 and 31. In fact, the heat-reactive paint has a high number of

28 Mott, C. F. (1974). Metal-insulator transitions. Philosophical magazine. 30 (2), 402, https://doi.org/10.1080/14786439808206565

surprising applications especially the the thermochromic wall paper shown here. After the temperature input - given by the higher temperature in the room or after touching the paper - the red flower starts to appear from below.
When night comes and the lower temperatures prevails, the colorful flower print slowly fades back to the original monochromatic colour of the paper.
Considering the message, this poster becomes a lot more impactful when its viewers stop being passive observers and start applying their own creativity to the surface through an active product experince.
These material qualities of this heat reactive paint encourage the final utilizers to reach out, touch, examine and enjoy objects through his sensorial perceptions.



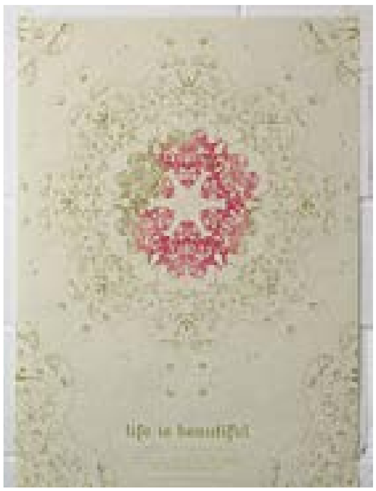




***Fig. 29, fig. 30 and fig. 31:*** *Life is Beautiful paper made of thermochromic inks by designer Shi Yuan. Source: https://dornob.com/heat-actived-paint-for-color-changing-interior-designs/*

***Fig. 32:*** *Thermochromic cover for smartphone. Source: https://www.amazon.it/custodia-Thermochromic-cambiamento-sensore-termico/dp/B071CDKBZ4*

### 2.3.3 Mechanochromics

Mechanochromc materials display a change in colour or transparency with a change in the mechanical stress applied to them. **These smart materials can respond to compressive, tensile or more complex forms of stress. The term piezochromic is also used in the literature to describe the same groups of materials.** [29] They are from metallic, ceramic and polymeric materials families. Some of them are irreversible and the switch on – or off – effect is present on some materials only.

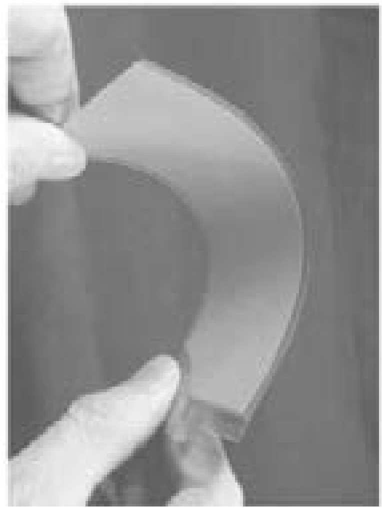
For instance, smart materials technology incorporating piezoelectric transducers was pioneered in the aerospace industry when there was a need to control vibrations of large structures like satellites and solar array panels as well as for isolation and noise control of high-precision equipment for radio frequency applications and in optical and microgravity experiments. In the last two decades, piezoelectric materials have gained significant interest in SHM (Simple Harmonic Motion).


***Fig. 33:*** *Mechanochromic materials. Source: https://www.youtube.com/watch?time_continue=53&v=UgGQJWRKRz8*
***Fig. 34:*** *Mechanochromic materials. Source: https://www.cam.ac.uk/research/news/flexible-opals*

**The SHM systems developed with attached or integrated piezoelectric transducers are aimed at both detecting and**

29 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. p. 47; Cham: Springer.

**characterising in-service damage and manufacturing flaws before they grow and propagate into critical failure modes. The prospect of the application of piezoelectric transducer systems in SHM thus spans into a number of major industries including aerospace, transport, civil, mining and energy production.**[30] There are also research activities that investigate the application of the technology to monitor the integrity of composite strengtheners and repair patches. Industry SHM solutions like SMART Layer and Active Fibre Composite (AFC) shown in fig. 35 are derived from the application of piezoceramics but with different transducer constructions. Viedt and Liew (2013, p. p . 449 - 479) said that **"the SMART Layer is made of piezoceramic transducers distributed on polyamide film with a printed circuit and has been reported in use for a number of composite applications. AFCs consist of unidirectional piezoceramic fibres sandwiched between interdigitated electrodes printed on polyimide film. AFC is mainly used for shape and vibration control of structures but has recently been recognised for SHM applications"**.[31] There are piezochromic paint for tennis, volleyball, basketball, and similar courts (fig. 36). Moreover, other two patents were granted to Unilever regarding a smart toothbrush. The toothbrush body incorporates a piezochromic liquid crystal cholesterol ester whereby the user is informed whether correct or excessive force is being applied during brushing. **The main intention of this product is to prevent damage caused to teeth and gums due to brushing too hard**.[32]



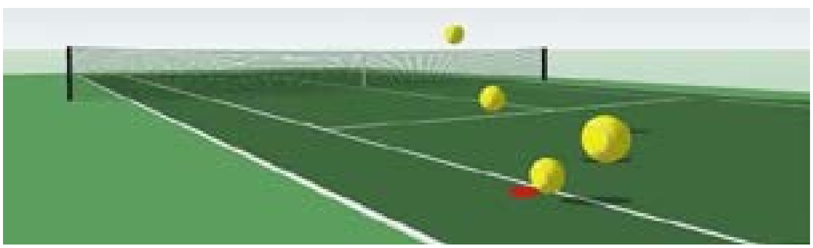


***Fig. 35:*** *Piezochromic SHM transducer solutions: (a) SMART Layer®; (b) Active Fibre Composites from Materials Systems Inc. Source: https://www.sciencedirect.com/topics/chemistry/smart-material*

***On the left: Fig. 36:*** *Mechanochromic concepts in sports field. Source: Materials that change colour*

30 Xinlin Q., Wenzhuo L., Yishou W., & Hu S. (2019), Piezoelectric Transducer-Based Structural Health Monitoring for Aircraft Applications, Sensors - Multidisciplinary Open Access Journal, vol. 19, 545. Retrieved from https://doi.org/10.3390/s19030545

31 Veidt M., & Liew, C.K. (2013), Non-destructive evaluation (NDE) of aerospace composites: structural health monitoring of aerospace structures using guided wave ultrasonics, Woodhead Publishing Series in Composites Science and Engineering

32 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. Cham: Springer.

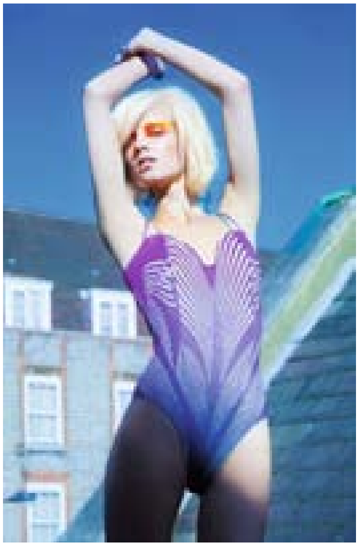


***Fig 37 (upper):*** *Sun reactive and water reactive dresses by Amy Winters*
***Fig 38 (lower):*** *Hydrochromic bikiny by Spinali Design*

## 2.3.4 Chemochromics

They are materials that change colour when exposed to specific chemical environments. They are from metallic, ceramic and polymeric materials families. The activation time can take a while. They are divided in diverse sub-families:
- Gas chromics - that react to gases
- Halochromics - that react to pH
- Hydrochromics - that react to water
- Hygro chromic - that react to moistures
- Solvatochromic - that react to solvents
- Other chemochromics - that react to chemical species, pathogens etc

***Gas chromic materials***
Gaschromics are based on the property of tungsten oxide thin films to color in the presence of hydrogen gas with a suitable catalyst. Gaschromic window construction follows a double pane model with a gap between the two panes. On one pane, a film of tungsten oxide is deposited with a thin layer of catalyst on top. Hydrogen gas is fed into the gap producing coloration of the tungsten oxide layer. To switch back, the gap is purged with another gas. Transmittance of 75-18% and Ts = 74-14% have been obtained, which is better than most electrochromic windows. The windows can colour with 0.1-10% hydrogen, which is below the flammability concentration. **The Fraunhofer Institute for Solar Energy Systems and Interpane has built a pilot production plant that can produce 1.5 m × 2 m windows. They have developed a small gas generator that can be incorporated into a wall, but the plumbing of the gas tubes for the window remains an issue**.[33]

***Halochromics***
A specific class herein is halochromic textiles, i.e. fibrous materials that change color with pH. Such halochromic textiles play an important role in the continuous monitoring and visual reporting of the pH with applications in various fields, such as wound treatment and protective clothing. **pH-sensitive**

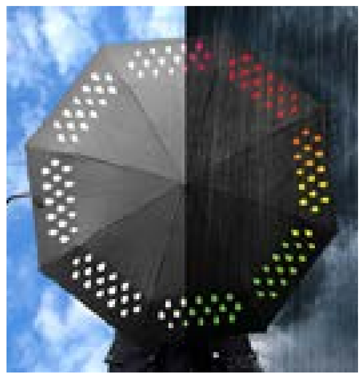
33 Lampert C. M., (2004), Chromogenic smart materials, MaterialsToday, 7 (3), p.p. 28-35, Retrieved from https://doi.org/10.1016/S1369-7021(04)00123-3

**nanofibrous nonwovens have high sensitivity and a fast response time and are mostly fabricated by introducing a pH-responsive dye via dye-doping of the feed mixture before fabrication.**[34]

### *Hygro-hydrochromics materials*

Hydrochromic materials are employed as coating for use on textiles. Their colour-shift effects are visible when they come into contact with water. The hydrochromic materials change colour when wet and they change back to their original colour when dried. The water-sensitive coating pigments can be screen printed onto cotton, polyester (fig. 39), nylon and blended or nonwoven fabric and other materials. They can be soft to the touch (fig.40) and also have excellent water resistance and rubbing fastness (in fig. 41).

**Fashion, health, and telecommunication industries are also pursuing the vision of clothing that can express aspects of people's personalities, needs, and desires or augment social dynamics through the use and display of aggregate social information.** [35] For instance, Joanna Berzowska , who is a Professor in Design and Computation Arts at the Concordia University in Montreal, is studying the use of conductive yarns and fibers for power delivery, communication, and networking, as well as new materials for display that use electronic ink, nitinol, and thermochromic pigments. The textiles are created using traditional textile manufacturing techniques: spinning conductive yarns, weaving, knitting, embroidering, sewing, and printing with inks.

*From the upper one to the lower one on the right side of this page:*

*Fig. 39: Hydrochromic cloths for children. Source: http://www.squidlondon.com/*
*Fig. 40: Hydrochromic leather. Source: https://www.pinterest.it/pin/507569820497036185/*
*Fig. 41: Squiderella di Squid London,2009 con inchiostro idrocromico http://www.squidlondon.com/shop*

34 Steyaert I., Vancoillie G., Hoogenboom R., & De Clerck K. (2015), Dye immobilization in halochromic nanofibers through blend electrospinning of a dye-containing copolymer and polyamide-6". Journal Royal Society of Chemistry, 1 (14), p. 4. DOI: 10.1039/C5PY00060B

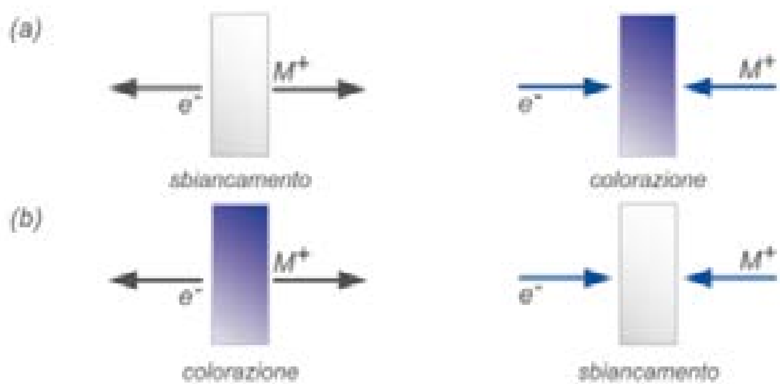
35 Berzowska J. (2015), Electronic Textiles: Wearable Computers, Reactive Fashion, and Soft Computation. Textile, Cloth and Colture, 3 (1), p.p. 58-75, Retrieved from https://doi.org/10.2752/147597505778052 63

*Fig. 42: Upper image: Here it's transparent and looks much like ordinary glass; Lower: Apply a small voltage and it turns opaque (blueish and dark). Source: photos by Warren Gretz courtesy of US Department of Energy/National Renewable Energy Laboratory (DOE/NREL)*

*Fig. 43 (a): e- and M+ ions injections and extraction to perform colour-shift from transparent to coloured configuration. Source: Materiali funzionali presentation (Politecnicodi Milano)*
*Fig. 43 (b): e- and M+ ions injections and extraction to perform colour-shift from coloured configuration to transparent one. Source: Materiali funzionali presentation (Politecnicodi Milano)*

### 2.3.5 Electrochromics

They are materials that change colour when a voltage is applied. They are from metallic, ceramic and hybrids materials families. The activation time is rapid. Related technologies include liquid crystals and suspended particle devices that change colour or transparencies when electrically activated. **The changes in the optical and chromatic properties can happen with electrical variations and electrical voltage (e.g LCD).**[36]
These materials, thanks to a little pulse of voltage, modify their transparent properties in a persistent or reversible way. This variation manifests as the passage from a transparent state to a situation in which the material is coloured and reflects - or absorbs - partially or totally the visible part and / or the solar part of the light spectrum. These technologies are characterized by different materials layers. The electrochromatism phenomenon manifests in diverse organic and inorganic compounds – that provide also oxidation and reduction reactions. The most used material is Tungsten ($WO_3$), which thickness range is equal to 200 – 300 nm. The electrochromatism provides a persistent and reversible change of the transparency through the simultaneous injection or extraction of small ions M+ and electrons e- with voltage pulse. When the electrical field is activated, the ions interact and generate coloured compounds that modify the chromatic spectrum of the material. These materials are deposited in




36 Minuto A., & Nijholt A. (2013), Smart material interfaces as a methodology for interaction: a survey of SMIs' state of the art and development. Conference paper: "Proceedings of the second international workshop on Smart material interfaces: another step to a material future." University of Twente. DOI: 10.1145/2534688.2534689

the form of thin films on a glass support or made of plastic material, creating a multilayer system (fig.47). Examples of electrochromic applications are represented by double pane windows with the ability to change colour upon contact with hydrogen gas in the gap between the two panes (fig. 42). The image represented in fig. 44 describes electrochromic glasses that change color under electric control. Electrochromics have also been very successful as dynamic antiglare automotive mirrors (fig. 44). Influenced both by styling considerations and by the aerodynamic benefits possible using flush glazing, car designers are making increasing use of glazing on automobiles. To give more details regarding this interesting and very innovative field, **the term 'Smart Glass', also known as intelligent glass, switchable glass, smart or switchable windows, represents a new technology enabling glass properties changes in accordance with external conditions like temperature, light, pressure or electricity.** [37]
Automobiles present both opportunities and challenges for large-area of chromogenic materials. **Opportunities include optical and thermal control of vehicle glazing along with optical control of rear view mirrors and privacy glass. Challenges include cost-effectively meeting automotive safety, performance, and reliability standards (fig. 46). Chromogenic technologies such as electrochromism, liquid crystals and thermochromism already exist.** [38] Switchable mirrors are now available for most major makes of cars. Several companies are working on switchable sunroof glazing (fig.44). The switchable glazing of the individual roof elements is represented in the upper image that was developed jointly by Webasto in conjunction with LG Chem and Merck using the ground breaking liquid crystal technology.


***Fig 44 (upper)***: Electrochromics antiglare mirror.
***Fig 45 (middle)***: Switchable motorcycle helmet visor. The spectra shows the change in visible properties with an applied voltage of 1.6 V. (Credit: C. Granqvist, ChromoGenics.)
***Fig. 46 (lower):*** Car smart glass.

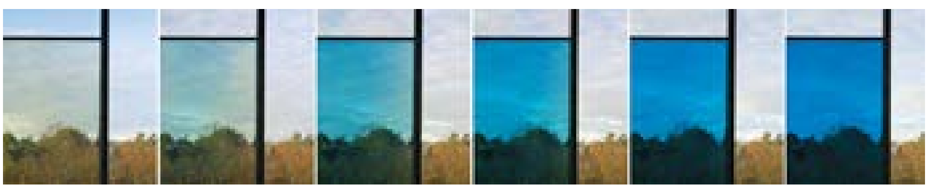


***Fig. 47:*** Switching Colors with Electricity. Source: American Scientist https://www.americanscientist.org/article/switching-colors-with-electricity

37 Smart Glass: Innovative Technology for the Future of Cars (2016), Last Access: 26/08/2019. https://www.qulix.com/about/blog/smart-glass-innovative-technology-for-the-future-of-cars/

38 Lynam N. R. (1990), Automotive applications of chromogenic material. Last Access: 26/08/2019. https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10304/1030404/Automotive-applications-of-chromogenic-materials/10.1117/12.2283607.short?SSO=1

### 2.3.6 Biochromics

**The use of chromogenic media for the detection of pathogens is now new but rather one of the commonly used methods for this purpose today. Chromogenic culture media, developed since 1990, target microbial enzymes and release coloured dyes upon hydrolysis.This approach results in the formation of coloured colonies which stand out against the background flora and allow the identification of pathogens easily.** [39] For safety purposes they are very used in food packaging industry for instance, to detect the foodborne bacteria, and toxines allerting potential users that the food is not helathy anymore. Some of these indicators are placed inside  in sealed package (e.g.) and are designed to alert consumers to chemical changes occurring within the product.They are sensitive to specific by-products that originate from deterioration reactions in the food.


***Fg. 48:*** Colour changes to a bromocresol green (BCG) sensor in response to a fish spoilage.. Source:  Color Changing Plastics for Food Packaging By Lizanel Feliciano (Ohio State University)

### 2.3.7 Others

Several other chromogenic materials which are sensitive to special stimulation such as radioactivity, electron beams, or infrared radiation.These materials have a direct effect on the visual appearance of an object, and present a large variety of possible inputs, therefore they can be used in a wide variety of applications.

39 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. p. 52, Cham: Springer.

| *CHROMOGENIC MATERIAL* | *CASE STUDIES IN ANALYSIS* *(shown in the previous chapter 2.3)* | *MAIN FEATURES OF OBJECTS MADE OF COMMON MATERIALS* |
|---|---|---|
| PHOTOCHROMICS | *Sensity Photochromic Lenses* ***(Fig 20****, page 33)* | *Normal lenses aim to allow the user to see better specifically in relation to their personal problem of sight.* |
| | *Bracelet indicateur de rayons UV* ***(Fig. 22****, page 33)* | *Bracelets made of plastics have mainly aesthetic purposes and no special values in terms of preciosity.* |
| | *Orange petal dress* ***(From fig.23 to fig. 25****, page 33)* | *Dresses consisting of textile fibers exhalt people's colours preferences, fit to the context of use.* |
| THERMOCHROMICS | *Colour-changing mugs* ***(Fig. 26,*** *page 35)* | *A normal mug is useful to drink some tea or coffee and its function is to contain liquid inside.* |
| | *Thermochromic table 'Linger A Little Longer' (****Fig. 28,*** *page 35)* | *An everyday table enables people to have normal activies and it represents a support for objects* |
| | *Life is Beautiful paper (****From fig. 29 to fig. 31****, page 36)* | *A wall paper used for cover the apartment wall has mainly decorative purposes.* |
| | *Thermochromic smartphone cover* ***(Fig. 32****, page 36)* | *Normal smartphone cover protect the cellphone inside from external damages and shocks.* |
| MECHANOCHROMIC | *Mechanochromic tennic court concept* ***(Fig. 36****, page 38)* | *A tennis court needs to allow the users to play the game in total comfort.* |
| | *Piezochromic SHM transducer solutions* ***(Fig. 35****, page 38)* | / |
| CHEMOCHROMIC | *Squiderella di Squid London* ***(Fig 41****, page 40)* | *Umbrellas need to repare users from rain and bad weather conditions.* |
| | *Water reactive swimsuite* ***(Fig 37****, page 39)* | *Swimsuites have aesthetic purposes protecting from exagerate sun exposure.* |
| ELECTROCHROMIC | *Smart window* ***(Fig 47****, page 42)* | *Normally, windows glasses could shield from light and protect the interiors from external conditions.* |
| | *Antiglare car mirrors* ***(Fig 44****, page 42)* | / |
| | *Electrochromic helmet visor* ***(Fig 45****, page 42)* | *The motorcycle helmets protect the user's head during driving for safety reasons.* |
| BIOCHROMIC | *Biochromic food packaging* ***(Fig 48****, page 43)* | *Food packaging needs to protect food from external bacteria and to isolate it from unhealthy conditions.* |

Table number 2

| *SMART PRODUCT CHARACTERISTICS SPECIALLY REFERRED TO THEIR CHROMOGENIC NATURE* |
| --- |
| *The photochromic lenses permit the end users to have a good vision also in case of change of light and in any situations, especially the most dangerous ones, as during car driving, for instance.* |
| *The photochromic bracelet allow the utilizer to be protected by UV rays because it changes colour due to an excessive exposure to the sun.* |
| *The smart dress made of stretch-cotton hand-screen printed is made for surprising the end users but most of all the other people around him.The photochromic screen-print changes from clear to purple sunlight.* |
| *A thermochromic mug allow the user to personalize it with his own photos that could be applied on it and the higher temperature of the liquid inside is underlined by the colour-shift of the mug surface.* |
| *The extra value of the smart table consists in the personal user-product interactions due to the colour-shift caused by user' body temperature. This creates an affection established over time.* |
| *The wall paper establishes a personal interaction with the user and it monitors the temperature in the room. It obliges users to investigate the colour effect increasing their knowledge of the material.* |
| *The thermochromic smartphone cover allow the user to know when the external temperature is too high for safety purposes related to the cellphone and if its overheating could occur. The aesthetics is more surprising in this case.* |
| *The mechanochromic tennis court is a concept that was developed to permit to know the intensity of the tennis ball smash and to understand better with the coloured sign if the ball fell into the field or not.* |
| *The aim of the transducer is to detect and characterise in-service damage and manufacturing flaws before they grow and propagate into critical failure modes. It permits a very good isolation and noise control of high-precision equipment for radio frequency applications for instance.* |
| *Hydrochromic umbrellas are funnier because they need to get wet to be more appreciated. For this reason, users are more stimulated to take it with them without feeling the negative aspects related to the product (e.g. the weight).* |
| *Hydrochromic swimsuites trigger the emotion of surprise and of amusement because they have extra values embedded in the material. They are characterized also by ironic and funny aspects.* |
| *Electrochromic glasses change color under electric control, they are useful in case the user needs a different light in the internal environment. He could choose them according to his pleasure and then, the glasses are flexible to user's needs.* |
| *Mirrors used in automotive field need to be antiglare to allow the driver to be safe, shielding external light that could create visual problems, meeting performance and reliability standards.* |
| *The switchable motorcycle helmet presents two colorations of the visor. It changes in visible properties with an applied voltage of 1.6 V and prevent the driver from dazzling light, then he is more safe.* |
| *The biochromic packaging changes to a bromocresol green (BCG) sensor in response to a fish spoilage. It allows the identifications of pathogens more easily than normal food packaging thanks to the colour-shift and then it guarantees healthy products to buy.* |

## 2.4 Theory of colours

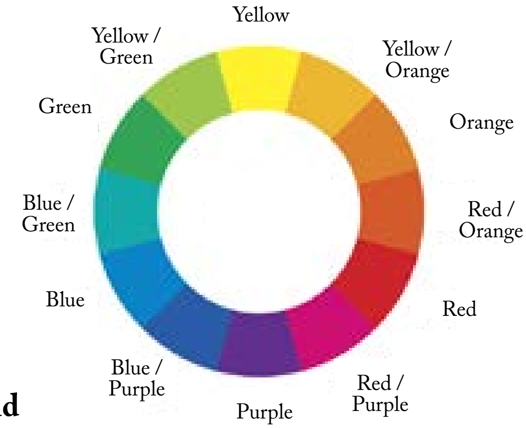



***Fig. 49 (ftom the top to the bottom):***

Chromatic disc with primary, secondary and terziary colours. Source: www.colorepuro.it

Colour is the first thing that meets the eye when the customer is shopping, so therefore colours are not only a matter of fashion and style, but also of strategy. **With trend research, relevant information can be obtained about what the consumer finds desirable to be conducted into modelling, material selections, colour schemes and processing techniques suitable for the target consumers.**[40] While colours and materials used to be often applied onto products at the end of the design process, now colours and materials are more and more taken into consideration in the early stages of designing. **Sometimes the design can be even completely driven by colours and materials, and in these cases, design related to colour, materials and finishes takes place even before the rest of the design process starts.** [41]
**Colour is one of the most fundamental property in vision. It is likely that colour vision evolved because it aids scene and object recognition as well as memory retrieval through predictive character regarding material properties and physical object identity.** [42] Thus, colour is perceived and interpreted as a meaningful environment signal, constrained and guided by our bodies' anatomy, and has extensive psychological and psychological effects. **In order to align the effects of colours with intended interaction concepts of tangible user interfaces, design may profit from knowledge in the area of colour psychology – the science that seeks to explain and predict how colours affects perception, cognition and behaviour.** [43] In this paper, colours psychology is not

40 Tan, J., (2011). Colour hunting. How Colour Influences What We Buy, Make and Feel. Amsterdam: Frame Publishers

41 Reiko Morrison (2010), Last access: 25. 08. 2019. https://thedesigncritic.wordpress.com/2010/07/21/color-material-finish/

42 Gegenfurtner K. R., Rieger J, (2000). Sensory and cognitive contribution of colour to the recognition of natural scenes. Current Biology, 10 (13), p.p. 805-808. DOI: 10.1016/s0960-9822(00)00563-7

43 Loffler D., Arlt L., Toriizuka T., Tscharn R., & Hurtienne J. (2016). Substituting colour for

investigated because the aim is to focus on perceptions and not on emotional responses. Only the surprise emotion is considered because is it strictly related to smart materials and their dynamic and not ordinary physical characteristics. Nevertheless, colour assumes real appearance, completeness only when it occupies a place in the project structure, the project construction that is considered in the whole system. As a product of design can be, for instance. The appearance and the colour interaction will be considered in this thesis that is the links that colours establish with other elements of our visual world. The interdependence of colour does not refer only to the interactions between colours, but colour appearance is also modified by the shape, position of the object, by the quantity and type of light that is reflected on it.
Colours do not depend only on factors that constitute the perception contest, but it interacts with them determining or influencing its perception. Then, if for instance, the shape and the type of contour modify the colour appearance, it is also true that our perception of the shape is modified by colours, in a reciprocal dual relation. For research purposes, it important to face the colour relatedness, in which colour exists for colour's sake, and therefore appears autonomous and not merely as accompaniment to form and shape. In fact, one of the aims of the thesis also consists in proposing some juxtapositions between different colours previously chosen for their meaning and to test the reactions they can elicit in the final utilizer if they change from one to another. To do that, the theory of colours is investigated, in which it is possible to see the main associations after user-colour interactions. Here, the principal relation that is analysed is the one between changing-colours materials and human emotions – that are strictly linked to colour meanings (and Meaning Experience), but also to Aesthetic Experience - linked to warm/cold sensations on visual level - leading to the final Emotional Experience. For this reason, the physical samples created are cylindrical (chapter 5.2) to let the testers concentrate only on the colour perception and its changing, instead of the physical shape of the sample that is the more neutral as possible and easy to handle. This is the main objective of the test that I am going to describe later.

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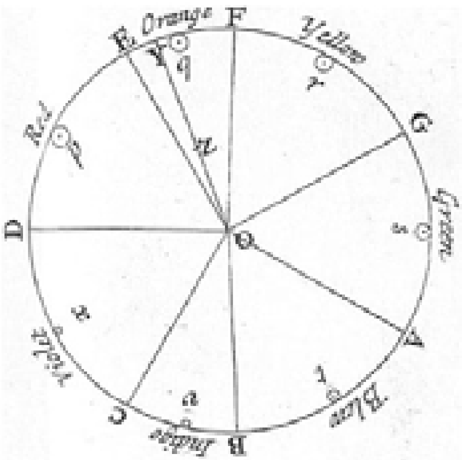
haptic attributes in conceptual metaphors for tangible interaction design. Conference: the TEI '16: Tenth International Conference CoEindhoven, the Netherlands. February 14-17, p.p. 118-125, DOI: 10.1145/2839462.2839485

### *The theory of colours*

The primary colours are red, blue and yellow and they are colours that cannot be produced by other colours mixture and for this reason they are consider "pure". The secondary colours are orange (red + yellow), green (yellow + blue), purple (blue + red) are obtained after mixing two primary colours. The tertiary colours are obtained after mixing a primary colour and a secondary colour (fig. 49). All the primary, secondary and tertiary colours are positioned in circle and they create the chromatic disk – that is shown below – and this scheme helps to understand in an easy and immediate way the various relations between colours and how they can be combined.  The colour wheel (fig. 50 and fig. 50) that is shown in two different version below, links between different colours based on the red, yellow, and blue content of each colour. It was first developed by Sir Isaac Newton (1642-1726) in 1666.[44]



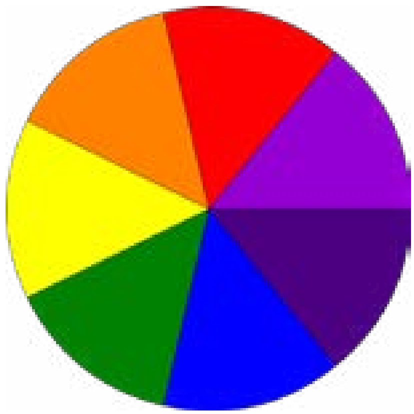



***Fig. 50 (left):*** Colours wheel by Isaac Netwon. Source: https://www.the-scientist.com/foundations/newtons-color-theory-ca-1665-31931

***Fig 51 (right)***: Color distribution of a Newton disc. Surce: wikipedia

44 Desktop Publishing, a companion site to CIOS 233 course at UAF. n.d., Last Access: 25.08.2019, https://cios233.community.uaf.edu/design-theory-lectures/color-theory

Colours have tints and shades. Tints are colours mixed with white and shades are colours mixed with black. This fact is visually explained in the image below (fig. 52).

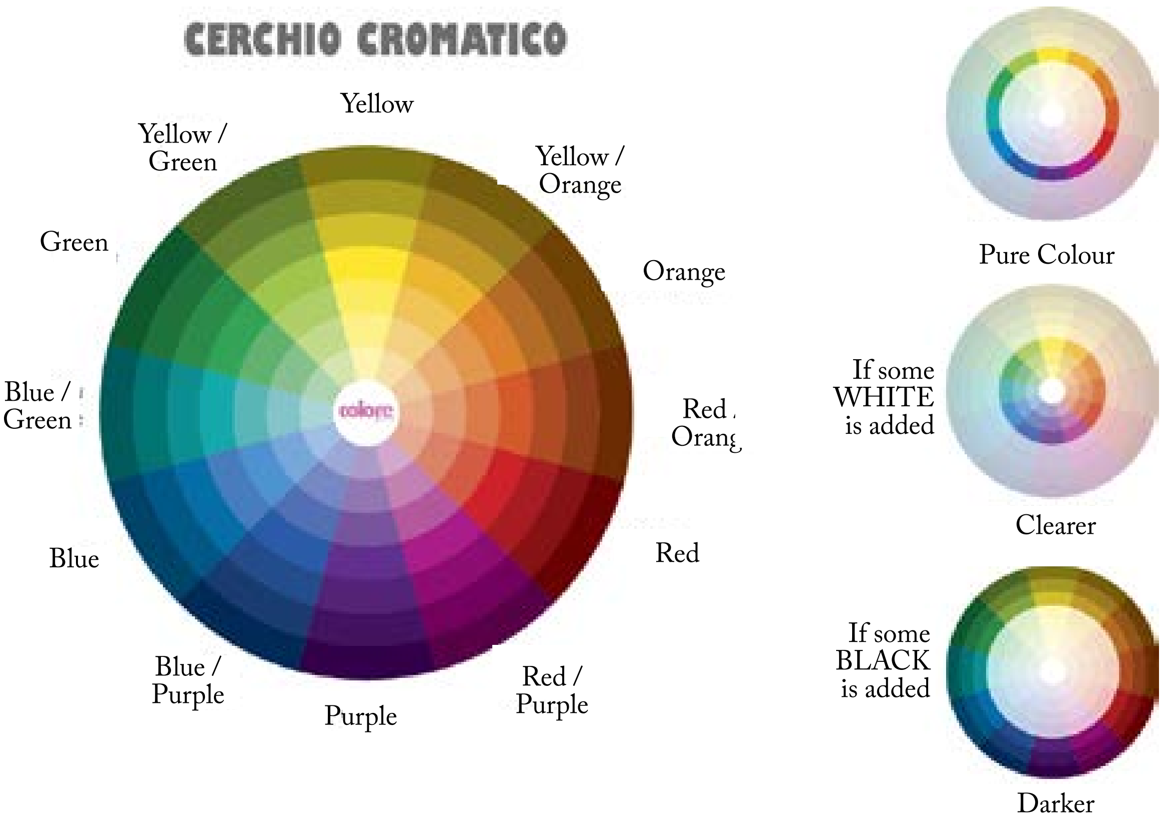



***Fig. 52:*** Chromatic disc with pure colours, tints and shades. Source: www.colorepuro.it

## 2.4.1 Colours combinations

The combinations of colours are explained below, (fig 53) and they are used to find out diverse colours uses. Colour combination also changes the nature and message of a single colour. Colour combining is like music – there is no exact meaning for a single colour, it is defined by the combinations. Colours should be chosen to deliver an enhanced aesthetic appeal and a better user experience. That means it's a good idea to think about what colour scheme designers will use at the start of the design process. The way that colours are combined can either add to the look and feel or detract from the final product. A colour scheme is the first element that communicates a specific type of message behind the design, on both visual and psychological levels. In fact, it is one of the most important elements because it reflects potential users' personal values and mood.

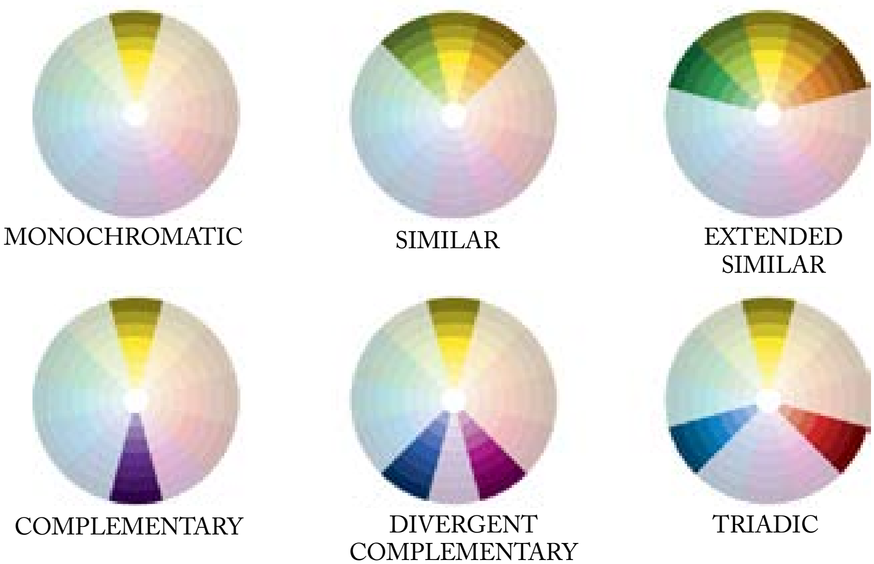



***Fig. 53:*** Colours scheme. Source: www.colorepuro.it

## 2.4.2 Colours and warm / cold sensations on visual level

Colours can be defined especially by their temperature sensation on visual level and they can be called warm or cold colours (and neutral colours). Temperature of colours is a specific characteristic that designers must use for better design purposes and they do not have to ignore it because it can be very useful and interesting. In fact, colours temperature can bring extra meaning to the final product of design. Warm and/or cold visual sensations represent an indicator that can be associated to different spheres of everyday life and it depends on the special way of being and of living of the final users. In fact, colour is a big issue in how people from different parts of the world could interpret design.

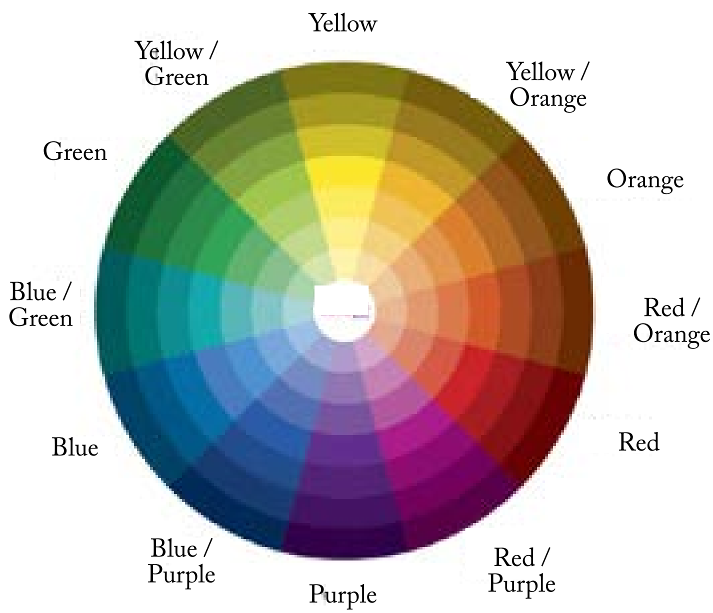



***Fig. 54 (left):*** Temperature colours disc. Source: www.colorepuro.it

***Fig 55 (upper)***: Warm colours.

***Fig 56 (lower)***: Cold colours.

Source: colorepuro.it

Designers' main issue about colours temperature is related

to the modality of user-product interaction through heat.
A team of Swedish designers at TEI, led by Södertörn University's Martin Jonsson, say that **temperature is a totally underutilized design material. After all, our daily lives are defined "by what are essentially acts of homeostasis—adjusting the temperature of our baths or showers, making sure our food and drinks are of the right temperature, putting on or taking off pieces of clothing".** [45]
There's a lot of human pleasure to be unlocked in heat, and right now, designers are ignoring it.

***The colours effects on tactile experience***

Starting from warm/cold colour sensations topic, it is interesting to understand what is the link between temperature on two different levels: touch and sight. The results of the majority of studies investigating the effects of colour on temperature perception suggest that hue plays the most prominent role, and brightness and saturation have no or less consistent effects. Two sources of origin of association are discussed: natural correlations and cultural conventions. In prominent temperature experiences in nature heat sources often appear in long-wavelength colors (fire, sun, blood flow to the skin in the face) and cold sources (forests, water) in short-wavelengths colors. This leads to the formation of a cross-modal correspondence in the first place, which is in turn expressed and reinforced through cultural habits like indicating temperature through red and blue in interior design.
Moreover, the natural correlations theory refers to primitive stimuli that human beings have since the beginning of times and it is linked especially to incongruent and congruent situations that are characterized by sensation of warmth and coldness on visual level and that are respectively red - cold or blue - warm in case of incongruent situations and red - warm or blue - cold in congruent situations. These two possible scenarios are investigated in the next chapter to better understand what are their influences in design field and how they can be used to design properly, knowingin advance people's feedbacks related to their use.

45 Campbell-Dollaghan K., (2016) The Future Of Tangible Interfaces: 5 Insights Backed By Science. Last Access: 25.08.2019, https://www.fastcompany.com/3056947/the-future-of-tangible-interfaces-5-insights-backed-by-science

# 3

# USER EXPERIENCE

# 3. UX in product design

## 3.1 UX and chromogenic materials

Even Donald Norman, the founding father of usable and understandable design, has now started to stand up for the role of emotion in design (Norman, 2002). As a result, it seems no longer sufficient for a product to function properly, to be usable and efficient, or to have an aesthetic appeal. Emotions need as extra value. People are emotional beings and products can address our emotions in multiple ways.
User Experience can be defined as a composition of Aesthetic Experience, Meaning Experience and Emotional Experience. The aesthetic experience is defined as the pleasantness of a product or a material in term of sensory properties, like the visual and tactile experiences for instance. **Talking about surface and touch, touch is the most analytical of senses, the furthest from sight. The message that it sends serves as a background to our system of representation – they do not become images. Corporal touch has to do with well-being and one's presence in space and there is no purely tactile aesthetics, except in the manual field. This aesthetics remains quite close to the psychological level and revolves around the sensation of a caress.** [46] Chromogenic materials can make users' Aesthetic Experience dynamic and interactive.
The Meaning Experience of materials refers to their symbolic attributions and their relations with people values and objectives. Functional materials add advices that constitute materials physical characteristics. These changes in the Aesthetic and Meaning Experiences – that refer particularly to the colour transformation with specific rapidity and colour intensity - make colour-changing materials totally different in term of Emotional Experience. For this fact the thesis emphasizes this special aspect of such materials.
Taking in consideration that in this paper only surprise emotion is going to be analysed as representative emotion that

46 Manzini E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.

the interaction experience starts with, the scheme below (fig. 57) sums up the principal keywords
related to common materials for UX experience topic. Product experience is how the product makes users feel (better or worse than before using it) and which emotions it provokes: love, disgust, fear, desire, pride, despair, etc. It includes three experiences aspects: Aesthetic, Meaning and Emotional ones, as previously described. The first two lead to the third one, the Emotional aspect, that is strictly linked to them.

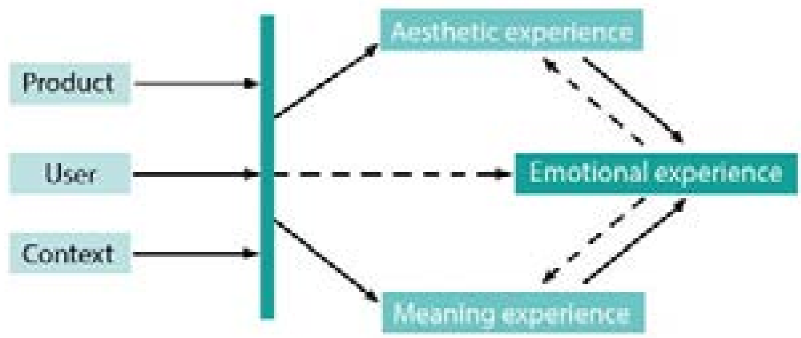



***Fig. 57:*** Desmet P. and Hekkert P. (2007). Framework of Product Experience

In the scheme represented in the following page (fig. 58) the product experience with smart materials is described. It differs a little from the first scheme above because some aspects change:

- The Aesthetic experience is now dynamic: smart materials unlike common ones, have two or more appearances according to the dynamic behaviour that varies with time and in response to field of energy. This is an important distinction that undermines both the user and the designer and challenges the suitability of instruments used for design up to now. [47]

- The Meaning experience and the Dynamic Aesthetic experience lead to an enhanced Emotional experience. With smart materials the object and the immediate environment change as do the way in which they are conceptualized, tested, design and produced. [48]

47 Addington, D.M., & Schodek, D. (2005). Smart materials and technologies for the architecture and design professions. Amsterdam [etc.]: Elsevier Oxford Architectural press.
48 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. p.5; Cham: Springer.

- The Meaning experience is enriched by information content – as in the common materials experience – and especially by the unexpected behaviour of smart materials that is characterised by the surprise effect they generate during the use.

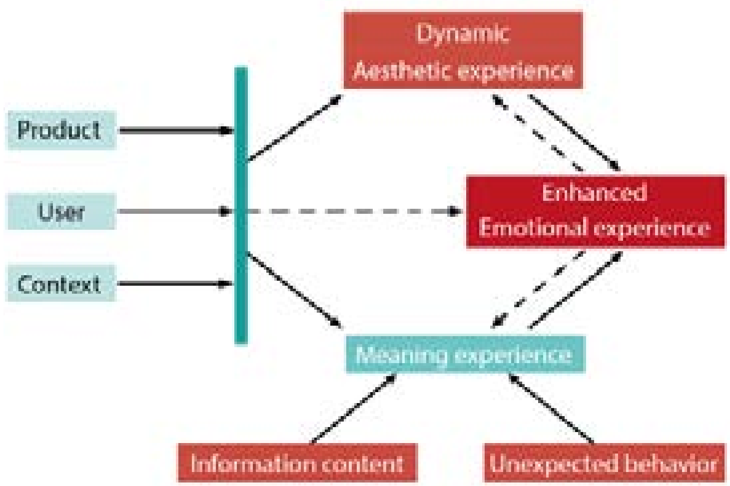



*Fig. 58:* Framework of Product Experience using smart materials. Source: nanotechnologies presentation. Politecnico di Milano

## 3.2 UX and surprise effect in product design

The importance of surprise is strictly connected to smart materials and particularly to chromogenic materials. This fact makes the user experience very valuable for the final users in terms of touch and sight because the colour-changing materials add extra value to the design product, especially from the interaction point of view.
It is important to let yourself be surprised by things that are all around you. The term that better portrays this situation is “serendipity” and it describes the discovery of something unexpected while searching something else. It is based on the capacity of let things go and the flexibility of let yourself be carried away by surprise. This mental condition is very useful in design field, especially from the designer’s point of view. It is not simple to design “surprise”, but the chromogenic materials open a new wide world to discover and create. In fact, the dynamic effect of chromogenic materials makes them alive matter and they really communicate an intended message to the potential user.
Our brain is programmed to react while facing something new and this is a characteristic we have because of our species. Surprise is a very brief emotion because it lasts only a second or less. **Then our brain starts the analysis of the new event and it passes to the next emotion - like sadness, anger, joy. Almost every emotion begins as surprise, because it implies that we catch something new in and relevant. It can be affirmed that the emotion of surprise is the presupposition of all the other ones**[49]. Moreover, the surprise emotion lasts until the user's evaluation of the stimulus is brought to completion because when the unexpected and surprising event is understood and determined by the user, the surprise effect ends and it is followed by another emotion that can be negative or positive, depending on the situations. The emotion that is consequent to

49 Zannoni M., (2015), Focus, Last Access: 25.08.2019, https://www.focus.it/comportamento/psicologia/perche-abbiamo-bisogno-della-sorpresa

the surprise one defines the overall user experience and it could be characterized by joy, amusement, interest or confusion, for instance.

**People's expressive manifestations of surprise are characterized by four types**[50] of facial appearances:
- Interrogative: it involves people's eyebrows and the eyes;
- Astonishing: that includes the facial changes of eyes and mouth;
- The least interested one: it involves the eyebrows and the mouth;
- The complete expression: all the three previous elements are involved in the experience (eyebrows, eyes and mouth).

In the global experience of surprise there are two different parts that could be noticed, on facial maifestations point of view: the surprise emotion and the emotion that follows. The preceding list above refers to the surprise emotion alone, that is considered in its specificity.

The user-product interaction, also called "product experience", can be defined as the global set of affective emotions and psychological effects that the design object has on the end utilizer. Then, it includes the perception, the identification and the cognitive associations of the users and their feeling and memories related to it. The product experience depends on the user's characteristics (as his personality, his interests and personal preferences and values) and on the object ones (its shape and colours, its function and the materials which is made of, etc). Another factor which the product experience depends on, is represented by the context of use (the precise moment in which the UX actions take place but also the physical environment around).

**Diverse types of product experience have been classified**[51] and they are:
- The instrumental interaction with an object: it occurs every time the product is used to fulfill a special purpose or action;
- The non-instrumental interaction: in which the relation with the product is characterized by playful aspects whitout a specific aim to achieve with it. It is based on the pleasantness of

50 Ekman, P., Friesen, W. V. (1975), *Unmasking the face. A guide to recognizing emotions from facial expressions*, Prentice-Hall, Englewood Cliffs, New Jersey, USA

51 Desmet P. M. A., & Hekkert P., (2007). Framework of product experience, International Journal of Design, 1(1), p.p. 57-66, Retrieved from https://diopd.org/wp-content/uploads/2012/02/frameworkproductex.pdf

the user-product approach.
- The non-physical interaction with the product: that refers to object anticipations through user's memories and imagination and it is linked to the user's emotive response.
The product emotions derived from the user-product interaction and they comprehend a very wide set of emotions, that are difficult to classify in a strict modality. They have been faced in previous studies, using three approaches to understand and catalog them better: Patrick Jordan's pleasure approach, Donald Norman's process level approach and the last one, that is like a mix of the previous two, that is the appraisal approach (that it will be more deepened also in the last chapter of the thesis).

Jordan[52] focused on four types of pleasure provoked by the product experience:
- physical pleasure (related to the sensorial perception);
- psychological (that refers to user's cognitive processes that are activated after the interaction with the product);
- ideological pleasure (related to the values that the design product symbolizes for the user);
- social (that focuses on people's encounters and human relationships).

The second approach is Norman's process level approach [53] based on the brain processes activated through the product experience, identifying three levels used to process information related specifically to different emotions. The three levels that he recognised are linked to three different design focuses:
- Visceral (that represents the most primitive and automatic one because it is connected to sensorial perceptions only);
- Behavioral (that governs the everyday human actions and it is performed without the people's consciousness, as the first one)
- Riflective (that is the most complex one, contemplative and conscious. It is linked to user's emotions, evaluations and interpretation). The three levels affect each other through a bottom-up scale (if the starting point is the sensorial perception), or a top-down scale (if the start is represented by a tought).

52 Jordan P. W., (2000). *Designing pleasurable products.* Taylor & Francis, London UK
53 Donald A. Norman, (2004). *Emotional design. Why we love (or hate) everyday things* Basic Books

The third and final approach is based on the cognitive theory of emotions and it especially focuses on the appraisal54 that represents an evaluation process through which the user automatically appraises the external events and stimula, that have a higher or lower valence in terms of personal level and that define the following emotive reactions in the user. In fact, the user's interest (keypoint of Jordan's approach) are mixed with the stimulus characteristics (valuable in Norman's approach). In the appraisal approach there are three user's interest levels:
- objectives (that answer the question "How much the stimulus is useful to fulfill a specific target?" and it is linked to the usefulness appraisal);
- tastes and personal preferences (that answer the question "How much the stimulus is pleasant?" and it is linked to the pleasantness appraisal);
- standards (that answer the question "How much the stimulus is morally acceptable?" and it is linked to the so called rightfulness appraisal).

After the following discussion related to the product experience and product emotions, the surprise effect is certainly part of the affective and emotive system previously described. Surprise emotion could be elicited by the user-product interaction and it characterizes the global product experience thanks also to the negative and positive emotions that follow it. The surprise effect could be derived also from the specific product features, from its meaning and performances of use. The surprise effect answers to a special appraising question that derives from the user's meeting with the unexpected that is cabable of breaking the user's expectations and certainties.

The very interesting subject - on which the thesis focuses on - refers to the possible design guidelines to adopt, for projecting surprise effect through chromogenic materials. Starting from the central topic of surprise, it is interesting to understand how it is possible to elicit it in the final user. Some directions are given in a very beautiful thesis focused on stategic surprise

54 Desmet P.M.A., (2010). Three levels of product emotion in KEER2010, Paper presented at the Proceedings of the International Conference on Kansei Engineering and Emotion Research, 2-4 March, Paris, France. Retrieved from https://diopd.org/three-levels-of-product-emotion/

modalities. [55] From a designer's point of view, the product can be conceptualized and realized according to some design rules:
- the designer who wants to create a surprising product needs to disregard the user's expectations;
- The product could appear as surprising due to ambiguous elements and visual illusions (related to its shapes and colours for instance);
- The design object can be characterized by changing features (as for the chromogenic materials, due to their dynamic properties that are activated after the user-product interaction);
- the designer must guarantee to the final user a proper balance between the familiar aspects of the object - that are recognizable by the end utilizer - and the ambiguous characteristics of the design product. Otherwise, the final user coul be too confused by the unusual features of the product and the following product-experience could not hit the target.

55 Monzio Compagnoni. F. (A.A: 2016/2017), Sopresa! Proprietà e stregie di un design inaspettato. Politecnico di Milano - Scuola del Design. Corso di Laurea Magistrale in Design del Prodotto per l'Innovazione. Retrieved from: PoliTesi

## 3.3 Chromogenic materials and common materials

Designers can develop a scenario of the sensory events that occur when a person encounters a product and may use this scenario as a starting point for the design of a new product.[56] Designers who intend to use smart materials and particularly chromogenic materials in their design, are within a field where materials matter is seen as an ensemble of information, interaction and perception. The condition that describes better the smart materials design is represented by matter seen as something fluid and prone to constant change.

Considering multiple sensory modalities during the design process is likely to create richer, more interesting and more engaging user-product interactions, because these products exploit the full potential of people's sensory connections with the surrounding world.[57] This can be done especially using chromogenic materials.

The main reason for using the chromogenic materials instead of the common ones is related to their peculiar characteristic of transformation. In fact, the dynamic metamorphosis they can express, can affect the user's mood and the way he interacts with the product. Does he learn how to use chromogenic design products in a faster modality because of their intrinsic physical characteristics?

Chromogenic materials exhibit a dynamic aspect that is absent from classical materials and are capable to sense and process information by themselves. For designers, this unveils opportunities to create unprecedented user experiences. By taking advantage of the versatility of these materials, designers can imagine a new relation between the user and the object. The sensory properties of a product

56 Rognoli V., Karana, E., & Pedgley O. (2014). *Materials experience fundamentals of materials and design*. Amsterdam [etc.]: Elsevier.

57 Rognoli V., Karana, E., & Pedgley O. (2014). *Materials experience fundamentals of materials and design*. Amsterdam [etc.]: Elsevier.

are essential in the user's evaluation and attachment toward it. [58] The fact that the physical properties of design objects are reactive, creates interesting applications in design field and they represent great advantages for designers, because chromogenic materials can extoll the user-product interactions.
Another advantage of smart materials over common ones is that their response is immediate and simple, while through common materials a complex system or interface would be required to give the same response, often with a larger delay.[59] This opens the possibility to a new way of conveying 'material immateriality'.[60] And for this reason, one of the main questions of the thesis refers to the possible faster learning and understanding modality of use of chromogenic design products instead of common ones. In other words, the term "material immateriality" should not be taken in a strict sense: chromogenic material objects do have a material aspect.
Then, the question of the immaterial is more related to an evolution, where the colour-changing materials are more than mere objects; they lead to a creative and interactive process. Immateriality is not an alternative word for emptiness; on the contrary, it could even be considered as a new state of matter. For Jean-François Lyotard the immaterial is matter; a matter which is subject to interaction and other conceptual processes. [61] The term "immateriality" here can be applied to smart materials and more specifically to chromogenic materials because of their transformation from one colour to the other hides a new meaning of understanding design products, and that mysterious sense is not tangible, but it is part of the immaterial sphere of human emotions and reactions.
Moreover, chromogenic materials are strictly linked to the miniaturized world of nanotechnology that can be perceived as

58 Passaro, C., Fiorani, E., Pedeferri, M. & Del Curto, B. (2013), Design the sensory: How Technologies and Materials Affect Sensations. The International Journal of Design Education

59 Lefebvre E., Piselli A., Faucheu J., Delafosse D., & Del Curto B., (2014), Smart materials: development of new sensory experiences through stimuli responsive materials. 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology, Milan, Italy. p.p. 367-382. ffemse-00995958v2f

60 Arnall, T., (2014), Exploring 'Immaterials': Mediating Design's Invisible Materials. International Journal of Design, 8 (2), p.p. 101-117, Retrieved from ijdesign.org/index.php/IJDesign/article/viewFile/1408/618

61 Grammatikopoulou C., n.d., Shades of the immaterial: Different approaches to the 'non-object', https://interartive.org/2012/02/shades-of-the-immaterial

immaterial.
Smart materials put our certainties in crisis. In fact, according to common sense, material is substance; the substance from which things are made, perceived by the senses, are characterised fundamentally by mass and volume. Even the terms materials and substance, due to the philosophical connotation, reminds something which exists itself in a permanent and stable fashion. **With smart materials, this idea is not valid anymore, starting from the relationship between material consistency and its appearance, between stable characteristics and their possible variations with time.** [62] With smart materials, the object and their immediate environment change, as do the ways in which they are conceptualised, tested, designed and produced. In fact, there is an added value in terms of performance and in terms of interaction with sensory stimuli that creates a more complex way of interaction with the objects using human senses.
**The presence of the object is, in a certain way, irrelevant in this matter, since, whether it exists or not, it is not viewed as an unchanging and stable structure, but rather as a changing dynamic.**[63] This dynamic condition is the extra characteristic that smart materials give to design objects that are interesting not only for their primary function but especially for the smart materials features they carry. So, they add meaning and value to the final design product.
To sum up, **the term "immaterial" is used to define the realm of the physically imperceptible; it can either be used to describe elements that need to go through different processes in order to be perceived or to shift the focus from the object to the process of creation and the ideas behind it**.[64]
**Integrating intelligence, autonomy and multi-functionality, these materials potentially permit the realisation of products with similar functional abilities while saving energy with respect to traditional systems. For example, labels using chromogenic technologies (already available commercially) are much more cost- and energy-efficient compared to other methods that depend on logistics,**

62 Ferrara M., Bengisu M.. (2014). Materials that change color smart materials, intelligent design. Cham: Springer.

63 Grammatikopoulou C., n.d., Shades of the immaterial: Different approaches to the 'non-object', https://interartive.org/2012/02/shades-of-the-immaterial

64 Grammatikopoulou C., n.d., Shades of the immaterial: Different approaches to the 'non-object', https://interartive.org/2012/02/shades-of-the-immaterial

**electronics, and communication technologies for the monitoring of temperature breaches in the cold chain of fresh, chilled, or frozen food, since they don't require sophisticated instrumentation or costly statistical quality control procedures.** [65]

65 Ferrara M., Bengisu M.. (2014). Materials that change color smart materials, intelligent design. Cham: Springer.

## 3.4 How to use chromogenic materials to create new user-product interactions

Designing objects for fun and pleasure can happen when the products information is shown in a colourful, funny way, always available to potential users' attention, so it can entertain instead of distracting. Chromogenic materials are capable of achieving these results. The shift from the inputs to the outputs catches the final users' attention and it indicates the urgency of use the product. Technology should offer to life something more than higher-level performances for various activities: it should add richness and delight. The difficulty of good-design products is not to annoying despite the routine of use. [66] Some objects are nice and funny at the beginning but after some time they become boring and they lose interest. Human being's brain adapts itself naturally to repetitive experience according to our spirit of conservation. If, as Donal Norman says, a tester is asked to look repetitive images, the activity of his brain would decrease with repetition. The brain starts to react again only when something new appears on the horizon. The real surprise effect of a product is very enjoyable only at the beginning of use but after quite sometimes the designer's challenge is to overcome the first experience of use. The hallmark of a good design is the one that stands the test of time.[67] For Donald Norman this topic is real and alive: how is it possible to keep alive the excitement, the interest and the aesthetic pleasure for an entire life? The answer to this question, he says, relies on the study of creations that overcome the challenge of time. In fact, he thinks that the longevity of the product derives from the complexity of the structure.
Smart materials add information content that is directly embedded in the material, grant it a special meaning and can produce, at least in the first user-product interactions, an effect of surprise. These changes in the Aesthetic and Meaning Experiences make functional materials totally different in term of Emotional Experience. The dynamic surface can be used as intelligent interface to reach and

66 Norman Donald A. (2004). Emotional design why we love (or hate) everyday things. New York:, Basic Books.
67 Norman Donald A. (2004). Emotional design why we love (or hate) everyday things. New York:, Basic Books.

add an extra value to design products. In fact, the surface is an area in which it is easy to express one's image and **identity**.[68] Culture thereafter rediscovered the value of surfaces and of the sensory variables which surfaces can bear (Manzini, 1989). It is always a recent topic even if Manzini wrote it in 1989, especially due to smart materials and their physical properties.
**For example, thermochromic paints and inks can be used on tables and seats to indicate that someone has been there, a flu mask that indicates the user has a fever; the thermochromic effect can be added to a large range of support materials as dyes, paints or pigments.** [69]

### 3.4.1 Design of product skin through reactive surfaces

It is important to focus on the surface of products materials because they are the first things users are going to interact with. **Recognition of a colour, a texture, the quality of a smell or taste – these are all the sensory activities at a different level from the recognition of a shape. They require less interpretation, they are linked to a relationship of direct proximity – colour is the decoding of a wavelength, texture is the decoding of a precise mechanical action. The sensation that emerge are analytic, the synthesis of the image comes later and sometimes never comes. Part of the activity remains infra-symbolic, eludes language, sinks its roots deep into our zoological origins.** [70]
Products material is very important and it must be carefully design in order to underline the product physical characteristics and features. Materials surface represents their first level of physicality – on visual and tactile levels for instance – the potential user will experience. **Underestimating the importance of the surface in order to exalt the purity of forms can be a specific aesthetic choice, but not a general law. A world of significant forms but of homogeneous and commonplaces surfaces would completely lack a dimension**

68 Manzin E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.
69 Ritter Axel. (2007). Smart materials in architecture, interior architecture and design Basel Boston Berlin: Birkhäuser.
70 Manzin E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.

**of sensory relationships.**[71] For these reasons one the possibilities for future innovative design can be the study on surface to obtain interactive, technological and smart new products. As Manzini said, the future behaviour of sensitive and communicative skin is entirely inscribed within miniaturized components whose operation possesses physical aspects that escape our perception. The design of skin, and therefore of the objects that are made with it, is chiefly the design of interactivity with the environment – a scenario for which we must prepare the stage, the sets, and the actors. Imagining the nature of these "individual objects" is another, new chapter in the history of design.
With dynamic surfaces and chromogenic materials, products can reach faster the potential users whose attention is captured by the colour-shifts of the material. The meaning and the function of chromogenic product is more evident in this way, more appealing because of the surprise effect of the unknown and not ordinary material physical characteristics of the product. So, the "elaborating sensory messages" that Manzini talks about in his book let the potential users to know rapidly the understanding of the design object.
**The variety of surfaces has become a design topic, and that surface quality is now determined for the most part independently of other formal and functional aspects. We are encountering, in short, the design of the relationship of closeness with objects. Closeness here should be taken in its lateral sense** - with reference to touch, for instance with thermochromic materials - **but also in its broader sense – as closeness in the process of elaborating sensory messages, in the way in which colour is "closer" to an object that form, because perceiving colours require a lower level of mental elaboration.** [72]

71 Manzin E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.
72 Manzin E. (1986). The material of invention by ezio manzini with a preface by françois dagognet. Milano: Arcadia.

## 3.5 Chromogenic trends in materials and design

In this paragraph the intent is to give some hints of design trends that are adopted more and more nowadays in chromogenic field. The aim is not to deepen the subject through case studies but to show once more the valuable characteristics of the colour-changing materials especially regarding people's safety and end users' protection and to sum them up.

Due to the special physical characteristics of these materials, the user experiences also changes if it is compared to design products made of common materials. In fact, there is a different way of activation, different final effect – visual, tactile, etc – and a different control of the product and its material.

Nowadays chromogenic applications in design world are limited by the more advanced fields and they are characterized by great investments of the research: automotive field, fashion and clothing textiles, sports tools and the very innovative smartphones and tablets areas. They are brand new materials whose physical characteristics are not ordinary and not very known by people and for these reasons they have still a lot of potentials to show. The fields previously described are in continuous evolutions, they include fundamental aspects of human life and for these reasons they are always more deeply investigated, also because they have always something new to offer in terms of amusement and practical functions.

In recents studies, the chromogenic properties are used to satisfy mainly information requirements such as security guarantee for babies and babies' mothers and in other important fields (as the automotive one, for intance); better materials service performances; aesthetic purposes linked to users' personal tastes and chromatic preferences. The extra values that chromogenic materials could add in faster and different ways compared to common materials are represented by emotions and especially the one of surprise that can be

triggered and driven by the special physical properties of these smart materials.
Safety design products also comprehend the automotive field and in fact, the technology used in this sports area represents special films which are inserted into the car glass that allow changing the transparency through electric control signals. This technical device is called and known as "smart windows" - windows whose luminous and solar transmission vary dynamically to suit changing climatic conditions - that have a potential application as energy-efficient automobile glazing. The intelligent glass is ideal as a driving assistance and a safety feature. The field of vision in cars will vary according to the driving conditions. For example, the images made by several cameras installed in the car will be projected to the side windows, eliminating blind spots and helping driver while parking. Measuring devices in windscreen are expected to avoid clouding. Temperature and humidity sensors will regulate car heater to prevent windscreens fogging up. The driver can forget bad visibility in winter. Traffic signs, warning notices will appear on the windscreen enabling more safety on roads. Furthermore, smart glass will also be able to track physiological activities of car drivers providing valuable assistance in order to prevent driving errors, for example, via micro sleep alarm.
Others chromogenic technologies include:
- Liquid crystal (LC) technology such as encapsulated LC devices consisting of small liquid crystal droplets encapsulated in a polymer matrix.
- Electrochromic (EC) technology - where transmittance changes under applied electric field or current - is also proposed for energy efficient glazing.
- A laminate constructions formed from two glass substrates that sandwich an electrochromically active medium, and all solid-state devices fabricated by deposition of electrochromic thin films onto a single glass substrate.

Another field in which safety must be guaranteed is represented by the aerospace market, there are likely to be many changes in the future. The aerospace industry is interested in the development of visors and windows that can control glare for pilots and passengers.
The children field is also strictly related to the topic of safety because designing for kids requires more care and precision.

The limits that designers must impose themselves are more and more strict. This fact is due to children's unpreparedness to dangerous and unexpected situation in everyday life. Just for naming a few products, there are thermochromic babies spoons with safety purposes to warn the proper temperature for feeding the children and thermochromic thermometer for bathing the babies that ensure babies' parent that the water temperature is the correct one. These case studies are going to be described later in the conclusive chapter, to support the final design guidelines that are going to be proposed in this thesis for projecting surprise.

Moreover, there is a game that involves the use of piezochromics: this is a mystery game intended for children, age 8 to 13. **The game involves several cube blocks made of an elastomeric material such as synthetic rubber (polyisoprene or silicone rubber). Each face of each block is printed with a piezochromic image. When players rub the two blocks against each other, a symbol appears temporarily on the faces that are being rubbed together, because of the pressure. One set of the blocks is the key to the symbols. The players try to find out what types of symbols are written on the blocks and what they mean. When they put together all the symbols on all sides of one or more blocks, and when they find out to which letters or numbers they correspond to, they solve the mystery.** [73]

The design products that represent new technologies and innovative versions of smartphones, tablets, etc are linked to the recent technological world of information and contents that drive human beings nowadays. This digital sphere comprehends computers ( both laptop PCs and desktop PCs ), smartphones, iPads and iPod, with always new interface modalities and very delicate tools of use. Today chromogenic materials are used in this field mainly for aesthetic purposes and for fun, even if some thermochromic covers for smartphone and tablet have the double objective of protecting user's from the device overheating and for surprising them due to their special colour-shift. This field focuses on products performances in terms of digital advances, safety purposes and innovative user experience.

73 Ferrara M., Bengisu M.. (2014). Materials that change color smart materials, intelligent design. p.p. 51 - 52; Cham: Springer.

# 4

# THESIS QUESTIONS

# 4. Design goals and questions

## 4.1 Are vision and touch independent or integrated systems?

Before getting into the central topic of the thesis, related to the proposal of several design guidelines for designing surprise effect using chromogenic material for UX, the initial step is to analyse the relation that exists between vision and touch through bibliographical researches and studies. Moreover, what it is interesting to investigate is how they are link to each other and how much they reciprocally influence each other.

### 4.1.1 Does colour influence the tactile experience?

The principal topic that introduces the starting point of this discussion, is what kind of influence exists between visual and tactile experience when humans start to physically know a new product or a design object. In fact, these two senses give qualitatively different information that maybe cannot be combined to enhance perceptual performances for the physical understanding of textures and materials surfaces.[74] Nonetheless, colour-shifts are here investigated as the principal modalities that could influence user-product experience and that could drive emotion such as surprise. Then, the two main human senses - vision and touch - represent the introductive point for giving the later description of the UX through colour-shift materials that could add an extra value to the final product experience.

### 4.1.2 Could every colour be linked to specific temperature levels?

The individual / universal connotations of warm and cold human sensations on visual level are here investigated. Could colours represent different temperature ranges from a universal point of view? Could the same colour be perceived as warm or cold by almost everyone?

74 Whitaker A., Simoes-Franklin C., Newell F. N., (2008), Vision and touch: Independent or integrated systems for the perception of texture?. Brain Research. N.d. Elsevier. School of psychology and Intitute of Neurosciences, Trinity College of Dublin, Ireland, p.p. 60-69, Retrieved from https://www.researchgate.net/publication/5269684_Vision_and_touch_Independent_or_integrated_systems_for_the_perception_of_texture

## 4.2 How is it possible to project the surprise effect in product design field using chromogenic materials?

To propose some design guidelines useful for projecting chromogenic and especially thermosensitive products whose main aim is surprising the final users, the tool used during the thesis development consisted in a thermochromic test (chapter 5.2) - characterized by six thermochromic samples and one questionnaire - to have some qualitative and quantitative answers to use as a tool for the closing point of the thesis.

### 4.2.1 Do colour-shift materials emphasize warm and cold aesthetic perception?

The main intent is to focus on different chromatic spheres and to understand the reasons why people associate a specific colour to a determined warm or cold sensation. The white and black colours will be also investigated in their meaning linked to visual colours temperature. Moreover, the colour-shift will be also analysed to comprehend if it emphasizes or not the warm and / or cold easthetic characteristic of products and materials.

### 4.2.2 What is the relation between chromogenics colour-shift rapidity and Surprise effect?

**In products characterized by an immediate use with a clear and easy functionality, usually low-tech products, the surprise effect can be appreciated a lot because they do not need any cognitive efforts related to their use (e.g. a vase, a chair, etc).** [75] But what happen then if the materials are smart and not common ones?

### 4.2.3 Does colour-shift rapidity communicate good and bad feedbacks for the final UX?

The main objective here is to comprehend how it is possible to design surprising products made of thermochromic materials using the rapidity of the colour-shift to obtain qualitative good feedbacks from the users trying

75 Monzio Compagnoni. F. (A.A: 2016/2017), Sopresa! Proprietà e stregie di un design inaspettato. Politecnico di Milano - Scuola del Design. Corso di Laurea Magistrale in Design del Prodotto per l'Innovazione. Retrieved from: PoliTesi

to avoid negative feedbacks related to the visual and tactile perception.
Moreover, what are the main characteristics and conseguences of negative feedbacks of usability?

### 4.2.4 On a global point of view, what are the main conditions to use for designing with chromogenic materials to emphasize the final surprise effect?

The thesis ends with several design guidelines represented graphically and supported by some literature to help next designers to focus faster on the valuable properties of thermochromic and hydrochromic materials that could be used to emphasize the surprise effect of their design concepts and products. In fact, the final aim of the thesis is to summurise all the chromogenics different physical aspects, already reported and described in the first parts of this paper, to give a global idea of the directions that designers could follow in design field using chromogenics.

5

# TOOLS FOR OUTLINING THE FINAL DESIGN GUIDELINES

# 5. The practical tools and strategy

## 5.1 Colour vs Temperature relation

### 5.1.1 The reciprocal influences of vision and touch

Bibliographical researches show contrasting hypothesis related to the hue-temperature relation. On one hand, they support the positive colour influence on the temperature sphere[76], and on the other hand they regard that colour could not affect at all the temperature area, then linked to the human tactile experience[77]. Both these thesis are characterized by visual-tactile associations that could be described as the incongruent one - e.g. red/cold or blue/warm - and the congruent situation - e.g. warm/red and blue/cold. Then, the following discussion focuses on how much colours enhance the human sense of heat and chill. Moreover, the two most representative colours are red and blue because they are the most easy to be understood and linked respectively to warmth and coldness[78].

The hypothesis about positive colours influence on temperature, mainly related to congruent situations (red - warmth and blue - coldness), is described by the natural associations derived by primitive human experience of natural elements (fire red, sea and sky blue). For proving this hypothesis about the previous colours temperature correlation, different tests and experiments were done using visual and tactile stimuli on testers in diverse modalities.[79] This first hypothesis represents a paradigm known as the hue-heat hypothesis (HHH). The association between colours and temperature exists and the testers take more time to answer during incongruent situations (red-cold, blue-hot) than congruent ones (red-hot, cold-blue). The hue-heat

76 Ho, H.N., Van Doorn, G.H., Kawabe, T., Watanabe, J., Spence, C. (2014), *Colour-temperature correspondences: When reactions to thermal stimuli are influenced by colour.* PloS one, 9(3). Retrieved from: https://doi.org/10.1371/journal.pone.0091854

77 Ziat, Shirts, Balcer, Rolison. (2016), *A century later, the hue-heat hypothesis: does colour truly affect temperature perception?* Conference paper: 10th International Conference, EuroHaptics, London, UK, July 4-7, DOI: 10.1007/978-3-319-42321-0_25

78 Ziat, Shirts, Balcer, Rolison. (2016), *A century later, the hue-heat hypothesis: does colour truly affect temperature perception?* Conference paper: 10th International Conference, EuroHaptics, London, UK, July 4-7, DOI: 10.1007/978-3-319-42321-0_25

79 See previous notes n.78 and 79

hypothesis **considers the change in the subjective feeling of the temperature based on the colour of the object. As indicated by its name it is mainly related to heat and has been reported by Morgensen and English in 1926 who showed no evidence of such interaction. The subject regained attention almost forty years later with similar results or affect too small to be considered as interactive.**[80] More recent, several research groups showed that colours can actually affect temperature and pain perception. **We can apply conceptual theory to realm of colours, proposing that following this approach empowers designers to use colours as a tool for successfully conveying both haptic attributes (e.g temperature) and abstract meaning (e.g intimacy) in tangible user interfaces.**[81] This study was conducted by researchers in Eindhoven and their aim was to focus on colour-temperature associations. **The results of the majority of studies investigating the effects of colours on temperature perception suggest that hue plays the most prominent role, and brightness and saturation have no or less consistent effects.**[82] The greatest apparent warmth is assigned to long-wavelength colours like red, while short-wavelength colours like blue appear to be cold. **Two sources of origin of this associations were discussed by them and they are natural correlations and cultural conventions.**[83] In prominent temperature experiences in nature, heat sources often appear in long-wavelength colours (fire, sun, blood flow to the skin in the face) and cold sources (forest, water) in short-wavelength colours. **This lead to the formation of cross-modal correspodences in the first place, which is in turn expressed and reinforced through cultural habits like indicating temperature through**

80 Ho, H.N., Van Doorn, G.H., Kawabe, T., Watanabe, J., Spence, C. (2014), *Colour-temperature correspondences: When reactions to thermal stimuli are influenced by colour.* PloS one, 9(3). Retrieved from: https://doi.org/10.1371/journal.pone.0091854

81 Loffler D., Arlt L., Toriizuka T., Tscharn R., Hurtienne J. (2016). Substituting colour for haptic attributes in conceptual metaphors for tangible interaction design. Conference: the TEI '16: Tenth International Conference CoEindhoven, the Netherlands. DOI 10.1145/2839462.2839485

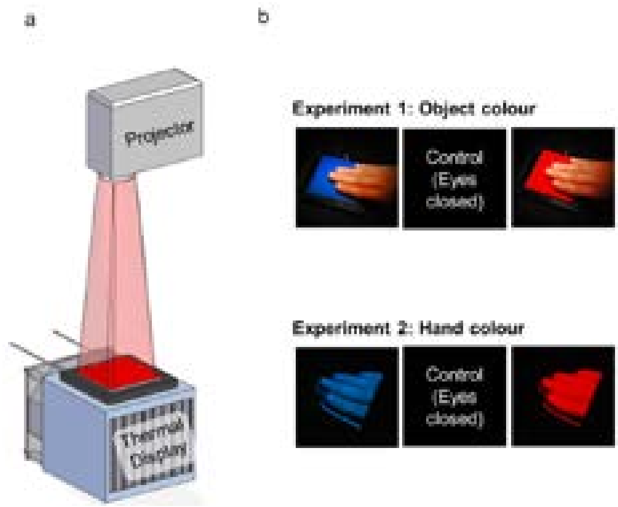
82 Ross R. T., (1938). *Studies in the psychology of the theater*. Granville, Ohio, The psychological Record

83 Ho, H.N., Van Doorn, G.H., Kawabe, T., Watanabe, J., Spence, C. (2014), *Colour-temperature correspondences: When reactions to thermal stimuli are influenced by colour.* PloS one, 9(3). Retrieved from: https://doi.org/10.1371/journal.pone.0091854

**red and blue colours in interior design.**[84] Several previous experiements related to colours vs tactile stimuli, showed that testers took more time to identify temperature during incongruent trials (red-cold and blue-hot). **This suggest two possible explanations: 1) when conflict arises between colour and temperature, participants' require more time for processing the information; 2) they actualy perceived the temperature as being less cold/hot when stimulus was incongruent.**[85] The starting researchers' hypothesis that under colour-temperature congruent conditions participants would have shorter contact times compared to incongruent trials was confirmed: red-warm and blue-cold congruenciy influences partecipants' response speed, so colour affect a little temperature perception. The negative point of view describes that there is no relation between red and warm perception and blue and cold sensations. So the congruence colour-haptic situations (red-warmth and blue-coldness) hypothesis are refuted: the two factors are not necessarily linked.

***In the first figure on the left (59a):*** the experimental set-up is described: the test system performed feedback control to the surface temperature. It could also selectively project colours onto the hand that was in contact with thesurface.

***In the figure (59b):*** the experimental conditions are described: the colour was manipulated by attaching blue or red colour paper onto the thermal display. In Experiment 2, the colour was manipulated by projecting blue or red colour onto the hand. In both experiments, an eyes-closed control condition was included.



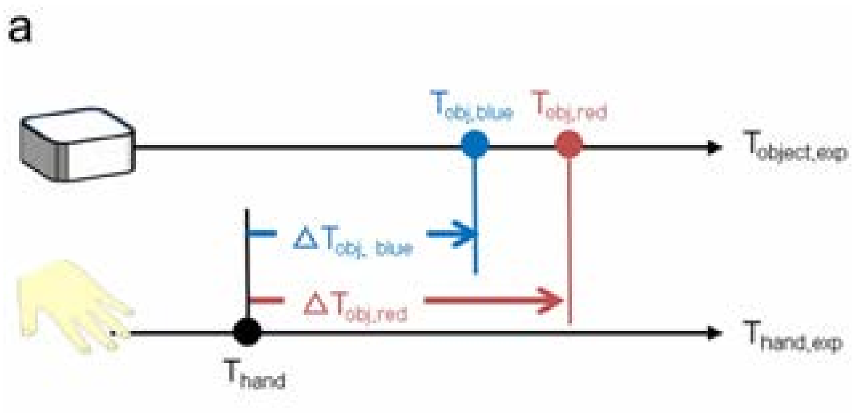

**The most representative test in this field is one that focuses on the "Anti-Bayesian" integration, which suggests that human brain integrates direct temperature input with prior expectation about temperature relationship between object**

84 Loffler D., Arlt L., Toriizuka T., Tscharn R., Hurtienne J. (2016). Substituting colour for haptic attributes in conceptual metaphors for tangible interaction design. Conference: the TEI '16: Tenth International Conference CoEindhoven, the Netherlands. DOI 10.1145/2839462.2839485

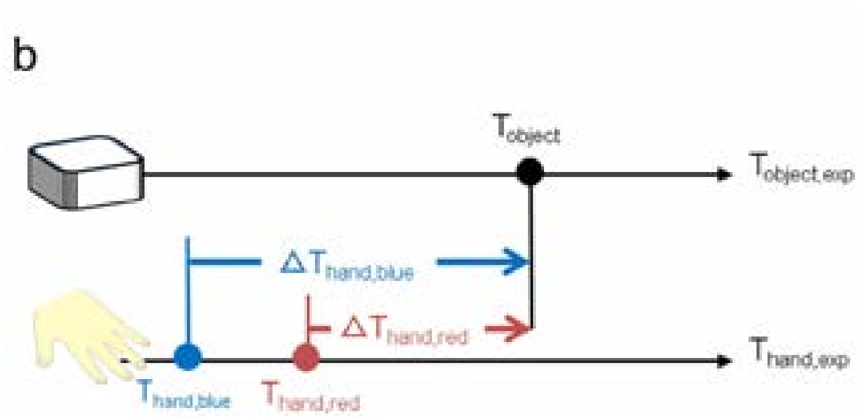
85 Ziat, Shirts, Balcer, Rolison. (2016), *A century later, the hue-heat hypothesis: does colour truly affect temperature perception?* Conference paper: 10th International Conference, EuroHaptics, London, UK, July 4-7, DOI: 10.1007/978-3-319-42321-0_25

**and hand in a way that emphasize the contrast between the two.**[86]

So, the experiment (fig.59 a and 59 b) that the Japanese researchers proposed found that a red object, compared to a blue object, raises the lowest temperature required for an object to feel warm, indicating that a blue object is more likely to be judged as warm than a red object of the same physical temperature.




***Upper figure 60a:*** Illustration of how object colours modulate temperature judgments




***Lower figure 60b:*** Illustration of how hand colours modulate temperature judgments

The red and blue colours were chosen here to maximize the evaluative potency of the colour information.

The two diagrams illustrate how object colours (fig. 60a) and hand colours (60b) modulate temperature judgments. The

86 Hsin-Ni Ho, Daisuke Iwai, Yuki Yoshikawa, Watanabe and Nishida. (2014), Combining colour and temperature: a blue object is more likely to be judged as warm than a red object, *Scientific Reports*, vol. 4, issue 5527, DOI 10.1038/srep05527

relative values of the expected hand (Thand,exp) and object temperatures (Tobj,exp) before actually making contact with the object are illustrated. Our brain compares the determine whether the object feels warm or not. The test demonstrates that not only the colour of the object (Experiment 1) but also the colour of the hand in contact with the object (Experiment 2) can have a direct impact on the temperature judgement of the object touched by hand. These findings indicate that colour is able to have an impact on the perceived temperature even when the temperature information is aquired via direct manual exploration. Specifically, the researchers found that a red object or a blue hand, compared to a blue object or a red hand, raises the lowest temperature required for an object to feel warm by about 0,5°C. The effects of the object and hand colours can be explained by a hypothesis wherein the object and hand colours modulate expectation of the relative temperatures of object and hand based on the prevailing red-hot / blue-cold association. People will tend to judge the touched object as less warm because the actual temperature difference would be smaller than the expected difference of a red object or a blue hand. Based on the same logic, people will tend to judge the touched object to be warmer when it is blue or when it is touched by a red hand, because the expected difference between object and hand temperature would be smaller than the actual temperature difference.[87] So, in the end, the results indicate that a blue object is more likely to be judged to be warm than a red object of the same physical temperature, which is apparently inconsistent with the red-hot / blue-cold associations.

87 Hsin-Ni Ho, Daisuke Iwai, Yuki Yoshikawa, Watanabe and Nishida. (2014), Combining colour and temperature: a blue object is more likely to be judged as warm than a red object, *Scientific Reports*, vol. 4, issue 5527, DOI 10.1038/srep05527

### 5.1.2 The link between colours and temperature levels

Starting from the bibliography and definition of light and colours, **visible light is a form of electromagnetic radiation with its frequency and wavelength that determine the final colour seen by human eye. The frequency of light in the visible spectrum is between 390nm – 700nm. The wavelength and frequency of light are closely related.** [88]

From the theory of colours and the bibliography related to it, the colours are markedly divided in warm and cold ones in the most known chromatic disc previously shown (fig 54, page 51). The possibility to adapt each colour to special range of temperature is still subjective: it depends on people values and personalities. In fact this theme is strictly connected to the diverse experiences - aestethic, meaning and emotional ones - that UX drives. The particular way different people perceive colours depends mainly on their personal values, materials and products symbolic attributions and past experiences that they had. For this reasons, the idea of creating a universal modality which is possible to divide colours with is not possible, due to the fact that a specific colour can be perceived differently by two diverse people and some **colours, such as purple and grey for instance, hold opposite meanings in different cultures.**[89]
The experiment related to thermochromic materials experience that is going to be described later in this thesis - in chapter 5.2 - will explain better this topic. In fact, during the experiment the evaluation of different coloured samples linked to warmth and coldness will give different answers.

88 Lucas J. (2015), Live Science, Last Access: 26.08.2019, https://www.livescience.com/50678-visible-light.html

89 Jacobs L., Keown C., Worthley R., Kyung-Il (1991), Ghymn, Cross-cultural Colour Comparisons: Global Marketers Beware! International Marketing Review, vol. 8, issue 3, Retrieved from https://doi.org/10.1108/02651339110137279

## 5.2 Thermochromic experiment - Focus on surprise effect

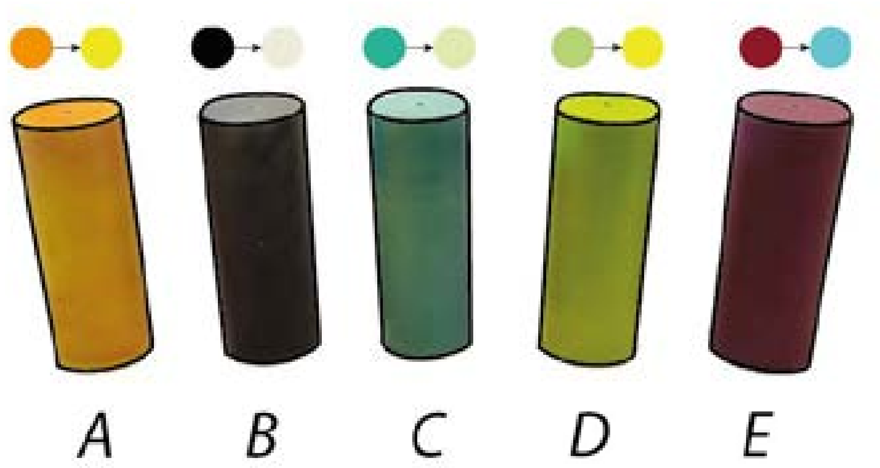



***Figure 61:*** Set of five thermochromic samples named from A to E that are linked to specific sensations of warm and cold on visual level.

Personal elaboration at the Ecole des Mines

### 5.2.1 Purpose

The main aim of this test consists in analysing the visual perception of colour-shifts related to the sense of surprise and unexpected of the colour-changing materials in analysis. The experiment is made with six thermochromic materials samples that vary the starting and final chromatic spheres due to temperature input. The testers are asked to take the samples in hands and to evaluate the colour-shifts, if visible, caused by the human body temperatures that can be different for each participant.

In the first pages of the questionnaire is asked to the testers to evaluate the visual sensations of warm and cold - linked to the visible colours of the specimens - in their personal opinions and the rapidity of the colour transformation and its intensity. It is particularly interesting to focus on the resulting answers of warm and cold nature of colours because the testers gave different responses associated to their personal experiences and memories of warm and cold things in their past and in their everyday life.

The central point of the questionnaire after analysing the testers' resulting answers is to know if it is possible to evaluate the user-interaction of smart materials and how people react to

them.
Furthermore, the colour-shift is analysed relating it to its rapidity. In fact, the more rapid the transformation of colour is, the better is the tester's feedback and responses. In some cases, the testers' negative feedbacks are noted down if related to not-working-samples and slow colour-transformations and the frustration of the user is visible during the tactile experience after 10 / 15 sec of user-sample interaction.
After the first moment of surprise in using the first thermochromic sample (A), the testers expect the same output for all the following samples and their user-experience satisfaction increases with colour-shift rapidity. The rapidity of the colour-shift is related to the sense of surprise only in the first moments of the test. After, the testers pretend faster responses from the samples and expect good feedbacks. Moreover, from the sample A to the sample E, the positive feedback from tactile point of view decreases. In fact, the sample E does not react well to the body temperature and it does not change colour if it is stimulated on tactile level because it has an activation temperature higher than 31°C as the samples C and D. For this reason, and also for the combination of colours of the sample E (that go from red / warm to blue / cold), after putting it into water, the surprise effect for this sample is the biggest of the tested ones considering all the samples prepared and considering also the different visual sensations of the starting colour (bordeaux / warm) to the final one (blue / cold).

### 5.2.2 Method

*Partecipants*
The final number of testers who were recruited are 62 testers (25 female), between 19 and 58 years old (Average Age 26,2 y.o.)

*Apparatus and materials*
The tools used for the perception analysis were thermochromic varnishes of diverse colours that have two diverse activation temperature 27°C for the samples A and B, and 31°C for the samples C and D. The colour of the samples varnished with

these thermochromic solutions changes after reaching the temperature of 27°C and 31°C. The powder used for covering sample E has a higher activation temperature so it worked only with hot water.
The samples used for the test are in PVC. This material was chosen because it is a good insulator and after touching it, at room temperature at about 23°C, the heat that passes from the material to the hand is a little and the tester does not perceive the cold sensation at the beginning. So, the change of colour can happen faster – than using a metallic sample for example, that is a good conductor.
The samples are all cylindrical and identical in dimensions: 40 x 100 mm. At first, they were subjected to a manual sandblasting process to let the first layer of varnish to attach better to the sample surface that at the beginning was too smooth. The first layer of varnish was plain white to allow the following thermochromic paint to be more visible and stand out. Then a second and third layers of varnish were used, and they were made by thermochromic powder SFXC mixed with water-based solution. The proper quantity of thermochromic powder SFXC mixed in water-based solution[90] was calculated knowing the total area of the cylindrical sample – equal to 125.000 $mm^2$ for only one layer of thermochromic paint. So, for double layer of thermochromic paint, the total area to cover was equal to 250.000 mm2 = 0,250 $m^2$.
Knowing that the varnish can cover 12 $m^2$ with 1 L, the proportion to know the exact amount of water-based solution to use – for two layers - is:

$$L : 12\ m^2 = x : 0{,}250\ m^2 > x = 0{,}0208\ L$$

The percentage of thermochromic powder to mix with 0,0208 L of colourless water-based solution corresponds about to 10% of the solution weight. For this reason, I firstly weighed the 0,0208 L of water-based solution and then its 10% weight of thermochromic powder to add was calculated. As last test step, hot water at around 45-50°C was provided in a glass bowl (fig. 63, on the right) to let testers to answer the final two pages of the thermochromic questionnaire. The bowl was in trasparent glass to allow testers to see the colour-shift of samples while immersing them in water.

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***Fig. 62:*** Thermochromic test in the office at the Ecole des Mines (Saint-Etienne, FR)

***Fig. 63:*** Thermochromic test in the laboratory at the Ecole des Mines (Saint-Etienne, FR)

***Procedure***

The testers were asked to sit down and they were instructed to read carefully the instructions of the questionnaire on the first page and answer the following questions. For any doubts the tester could have asked the supervisor clarifications, if needed. It was not a time test so the testers could take their own time to answer the questionnaire questions.

*Test phase*

To start, the testers were asked to take in hand initilly only sample A and sample B and to note down and to describe possible changes in the materials surface after the tactile experience, in a paper questionnaire that was previously prepared. They could describe the two samples in therms of physical and aesthetic appearance and to explain the scientific reasons behind the colour-shifts of the samples (if they saw it) in open questions.
The second part of the questionnaire refers to personal question about colour and chromatic perception with a focus on colour temperature evaluation of certain given colours **(black and white were part of the evaluation).**[91]
The third part of the questionnaire consisted in:
- testing the colour temperature of the samples before and after touching them;
- evaluatinge colour-shift rapidity;
- evaluating the intensity of colour-change (how much the final colour is evident after the thermochromic transformation).

The last part analyses the surprise effect during warm water-samples interaction (with closed response questions) and the comparison between tactile experience and water one. Testers were requested to describe what they like or did not like about the two experiences in open like-dislike questions using keywords and brief sentences. The water was provided at high temperature - 45°C or higher - to have a total different effect compared to the tactile experience previously tested. With water in a bowl the colour-change is more rapid and faster and the contrast between the starting colour and the final one are more visible and evident on the sample, after deeping it in hot water. Moreover, the evaluations of tactile experience and wate-interaction allow me to understand which of the two UXs gave better results in terms of surprise - linked to colour-shift rapidity and negative visual and tactile feedback - and testers' personal involvement and emotive partecipation, which experience they liked the most and why.

91 Wright A. (2018-2019), Last Access: 26.08.2019, http://www.colour-affects.co.uk/psychological-properties-of-colours

### 5.2.3 Data analysis

The results represented by the testers' answers were analysed from qualitative and quantitative points of view: what kind of responses they gave and how frequent the same answers were repeated among the tester in examination. The answers more recurrent establish a certain focus on the kind of testers' feedbacks they were related to.
Then, according to whether the same resulting answer was repeated more than five times in the overall questionnaires evaluations, it is taken in special consideration for the purpose of drawing the thermochromic experiment conclusions. In fact, considering the total amount of testers equal to 62, the five-time-repeated question stand for 1/12 of global testers number who gave that particular feedback. The same order of questions and test passages were used for all the testers, who could take their own personal time to perform the thermochromic experiement. The test lasted approximately 15-20 minutes on average.

### 5.2.4 Results and testers' ratings

***Introductive questions about samples A (orange > yellow) and B (black > white)***
The data show that the testers described the colour-changes of the sample A and B after tactile experience, as a modification in clarity and fading of the starting colour (orange to yellow and black to white). 29 testers on 62 ones noted that the colour of the sample changed in the area where it was held. More than half of the testers (34/62) answered that they did not know what happen during the tactile experience with sample A and B but when it was asked them to guess what was the input of colour modification, 50 testers on 62 answered with the correct answer (the two sample changes due to human body temperature).

***Personal questions about colours perception***
Most of the testers (35/62) had more than one favourite colour in their daily lives or one favourite colour (22/62) and they are especially blue (for 35/62 testers), green (for 24/62) and red (19/20)

that are two primary colours and one secondary colour but **the ones that are more visible outside and most used in pubblicity and marketing strategy because it drive safety and trust**.[92] Moreover **in colour psychology this colour is linked to calme, tranquillity and associated with water and peace. Blue causes the brain to release chemicals that calm, but use too much blue and that sends a cold and uncaring message. Red is linked to passion, intensity, love and danger and green evokes health and nature.**[93]

### *Colours Temperature*

When testers were requested to evaluate the warm or cold sensations of **colours previously prepared**[94], they answered that blue (for 58/62 testers), grey (for 53/62 testers) and light green (for 37/62 testers) are cold colours; brown (for 39/62 testers), orange and red (for 60/62 testers), pink (for 46/62 testers), and purple (for 32/62 testers) are warm colours. White (49/62) and black (43/62) are both cold colours for the majority of the testers even if some of the testers did not answer because they consider them neutral colours or non-colours (for white 3 tester did not answer; for black 2 blank answers).

Talking about the question asked about the warm / cold sensations before touching the samples, the testers answered coherently with the answers given in the previous personal part (the one related to warm or cold sphere colours evaluation):

- The starting colour of sample A (orange) was considered warm (for 60/62 testers) and after touching it, the colour-transformation to yellow was considered warmer (for 30/62 testers) with 2 testers who did not get the visual feedback;
- The starting colour of sample B (black) was considered cold (for 47/62 testers) and after touching it, the colour-shift of the sample to white/grey was considered colder (for 40/62 tesetrs) with 3 testers who did not get the visual feedback;
- The starting colour of sample C (sea blue) was considered

92 Psicologia Del Colore: Come Vengono Usati I Colori Nella Comunicazione E Nella Pubblicità (2018), Last Access: 25.08.2019, https://minimegaprint.com/blog/psicologia-del-colore-come-vengono-usati-colori-nella-comunicazione-e-nella-pubblicita/

93 Ferreira N. M. (2019), Color Psychology: How Color Meanings Affect Your Brand Last Access: 25.08.2019, http://www.empower-yourself-with-colour-psychology.com/cultural-colour.html and dirigodev.com

94 Psicologia Del Colore: Come Vengono Usati I Colori Nella Comunicazione E Nella Pubblicità (2018), Last Access: 25.08.2019, https://minimegaprint.com/blog/psicologia-del-colore-come-vengono-usati-colori-nella-comunicazione-e-nella-pubblicita/

cold (for 56/62 testers) and after touching it, the colour-changing to light green was considered colder (for 32/62 testers) with 2 testers who did not get the visual feedback;
**o** The starting colour of sample D (electric green) was considered cold (for 32/62 testers) and after touching it, the colour-shift to yellow was considered warmer (for 29/62 testers) with 4 testers who did not get the visual feedback. But in this case the half answers (29/62 testers) were related also to the coldness of the colour-shift. This fact can be explained due to the similarity between green and yellow and due to the not so evident contrast between the starting colour and the final one.
**o** The starting colour of sample E (bordeaux) was considered warm (39/62) and after touching it, the colour-shift to light blue was considered colder (for 36/62 testers) with 7 testers who did not get the visual feedback. Most of the testers did not see the colour-change but only that the starting colour was fading, getting lighter.

The particular way different people perceive colours depends mainly on their personal and cultural values and their own past experiences that they had. That is why colours cannot be perceived and sense from a universal point of view but they especially depend on each person's way of perceiving the world around her / him. And the previous results show this fact.

The things they liked less about tactile experience with the samples are mainly related to the negative visual feedbacks: when the samples did not change colour due to low thermal conductivity of the samples material (PVC). The worst visual and tactile feedback was related to sample E, in fact several testers noted that they did not like it at all. Testers did not like the slow colour change of the material, because after the first two sample A and B that were more reactive due to a lower activation temperature (27°C), the other ones are slower and required more time to be held and change their colour.

Regarding the warm water experience, testers like the fact that the colours on samples were very vivid and evident and the rapidity of colour-shift was very fast compared to the one had during the tactile experience. The surprise effect during the water UX was reported by several testers because it was more fun, especially with sample E, whose colour-changing nature was more appreciated.

The aspects related to water UX that testers did not like were very poor, in fact 34/62 testers left empty the space for describing the negative facets of water experience. Moreover, testers did not like very much the colour-shift fastness of sample E that shows, after the water immersion, a very fast change to the original colour (due to the thermochromic powder used and the combination of thicker layer of plain blue common varnish and thermochromic red powder).

### *Surprise effect*

The globally test experience was surprising for 45 participants on 62 and amusing for 58/62 testers. The most surprising samples are specimens A (for 54/62 testers) and E (for 56/62). During the water-specimens interaction, the first one (A) was described as surprising because it was the first sample the testers interacted with and the surprise effect was more genuine and and authentic.
Sample E was surprising because in the first experiment step, the tactile experience was frustrating for the testers and they could not see any colour-shift on sample E surface. This fact increased a lot the curiosity and expectation for that specific specimen. Moreover, its starting colour (bordeaux) and the final hue (lightblue) belong to different temperature spheres on visual level (respectively to warm and cold ones) and the constrasting visual effect is very evident. The surprise effect related to sample E was based on these reasons.
Despite good final results linked to surprise effect, the less surprising samples were sample B and sample D. Specimen B was surprising for 43/62 and sample D was surprising for 37/62, not bad results but globally the worst. The reasons behind this fact are connected to the non-coloured nature of specimen B that shows black-to-white colour-shift. For several testers as for colours theory, black and white are neutral hues with very special visual characteristics compared to colours in general. Sample D was not so well-described by the testers and it was the least surprising sample because the starting colour (electric green) and the final one (yellow) were very similar in tints and shades and the colours contrast was very poor, in this case.
The main conclusions that were collected after the experiment confirmed that the contrast of colours create a better response in the testers during the user experience. The sample E could be

taken as the representative example: the diverse chromatic spheres between the staring colour and the final one give more visual contrast capturing the attention of the user at first glance. The user experience links to surprise effect and positive feedback, in fact the colour-changing with water from bordeaux to light-blue colour was very loved by almost all the testers. The necessity of a rapid feedback cannot be underestimated in this discussion because the negative feedback about visual and tactile experience is faced in frustration by the testers. The non-colours or neutral colours like white and black are considered as cold colours, even if they represent the opposite topic, in fact white is considered as the complete set of all colours and black is the absence of light and it absorbs all the colours of the visible spectrum.

## 5.3 Students' workshop at the Ecole des Mines de Saint-Etienne

### 5.3.1 Purpose

The students are asked to redesign existing design products or propose totally new immaginative ideas and concepts in sports field and children field. The workshop focused on these two research areas because they made possible to narrow the analysis field down, to obtain better results and let the workshop be more interesting, due to the always new discoveries in these areas of interest. Moreover, the sports and children products are very interesting nowadays because they provide many design starting points and cues. The main points of the research in these types of applications are related to changing-colour experience. Then, the workshop analysis focuses on the relation between the contrast of colours – used for sports / children tools and clothing - and a better response and feedback in using the design product and sports activities.
The main aim of the workshop consisted in testing students' background knowledge about chromogenic materials in general and thermochromics in particular and to get some hints and suggestions to start drawing my chromogenic design guidelines, that represent the conclusive point of my thesis.
The students' concepts could not be used in the end because they were already existing concepts or they were too imaginative but they helped to know which was their background in this smart materials field. For these reasons they are not going to be explained in detail but the workshop iter prepared is going to be described, with a special focus on User Experience tool such as the Honeycomb Diagram for instance.
The students were introduced to the workshop activity with a presentation to get to know the main materials information.
They tried the thermochromic experiment to get the topic in a more physical way and they were asked to evaluate several existing case studies on papers linked to chromogenic materials in sports and children field.

## 5.3.2 Method

***Partecipants***

The participant were 16 students from Master in Perspective Design at the école des Mines in management course and materials engineering (9 Male and 7 Female between 21 and 30 years old with different nationalities: 12 French, 1 Iranian, 1 Marochan, 1 Tunisian, 1 Algerian).

***Procedure***

The workshop consisted in the evaluation of the following case studies, the thermochromic samples test previously described (in chapter 5.2) and the final concepts activity. The evaluation of the case studies - existing thermochromic products from sports and toys field - that were previously chosen, consists in analysing different products with a list of adjectives in the first morning activity. In the afternoon the students were asked to produce practical sketches and papers to describe their idea of new application in design field: it could be a redesign of the case studies previously analysed or a total new product with specific functions linked to sports or toys field.
The adjectives used in the evaluation of the case studies are the same adjectives that the students are going to use in the final design activity questionnaire and were related to the honeycomb diagram that is going to be described later (fig. 64 on page 99). The case studies can simplify their approach to the final design concepts activity about chromogenic applications design and at the same time the students could analyse diverse existing applications of chromogenic materials. So, if they never got in touch with them they can get some information contents about chromogenic materials, and from the presentation used as introduction to the workshop topic, too.

***Training phase***

The workshop started with my introduction presentation about chromogenic materials and their existing applications nowadays. Then, during the morning there were two parallel activities: the evaluation of several case studies about existing chromogenic application that the students did individually on papers already prepared. At the same time, each student, one by one was asked to test the thermochromic samples and to

answer the questionnaire in another room.
During the afternoon, after lunch break, the design activity took place. The students worked in couples and at the end of the activity they answered a self-evaluation questionnaire on which they had to sketch their own ideas and concepts and define them with adjectives on the papers linked to the honeycomb diagram (fig. 64). The question related to it consists in imagining some new possible applications for chromogenic materials in design field. The limit is to focus on and design for sports people and children.

### *Test phase – Questionnaire structure for the final design activity*

The questionnaire gives some guidelines to define the final application product made of chromogenic materials. In the first page there are some general personal information that the two testers must fill that refers to their gender, age and nationality. Then, there are some instructions to use the questionnaire that the students must read before starting the activity. In the second page there are six column and the students must choose two adjectives for each column to describe their own chromogenic product after the activity to self-evaluate their own works. The column and the related adjectives refer to the Honeycomb diagram by Peter Morville that is described below (fig. 64). The columns are describe later in this paragraph (pag. 96).
The third page the students can draw their own sketches of the application they imagined and then they must specify which kind of chromogenic materials they used for the application and its input. The fourth and final page presents some questions related to their knowledge of chromogenic materials and the characteristic they chose to describe their own chromogenic application.

### HONEYCOMB DIAGRAM by Peter Morville

User experience honeycomb is a tool that explains the various aspects of user experience design. Since there are many aspects of this field far beyond usability, Peter Morvile felt that this new diagram would help to educate clients in companies.
The honeycomb helps to find the proper balance between the different areas that represents various attributes of the final design product in terms of UX.
**Each facet of user experience design can be defined by this**

**diagram as such:**
**- Usable: the system in which the product or service is delivered needs to be simple and easy to use. Systems should be designed in a way that is familiar and easy to understand.**
**- Useful: a business's product or service needs to be useful and fill a need. If the product or service is not useful or fulfilling user's wants or needs, then there is no real purpose for the product itself.**
**- Desirable: the visual aesthetics of the product, service, or system need to be attractive and easy to translate. Design should be minimal and to the point.**
**- Findable: information needs to be findable and easy to navigate. If the user has a problem they should be able to quickly find a solution.**
**- Accessible: the product or services should be designed so that even users with disabilities can have the same user experience as others.**
**-Credible: the company and its products or services need to be trustworthy and reliable.**[95]

Each application will be different based on the balance between context, content and users. But, by keeping all these points in mind it is easier to define priorities. For this reasons the honeycomb diagram represents a valid tool to be used by designers as a guideline during all the design process.

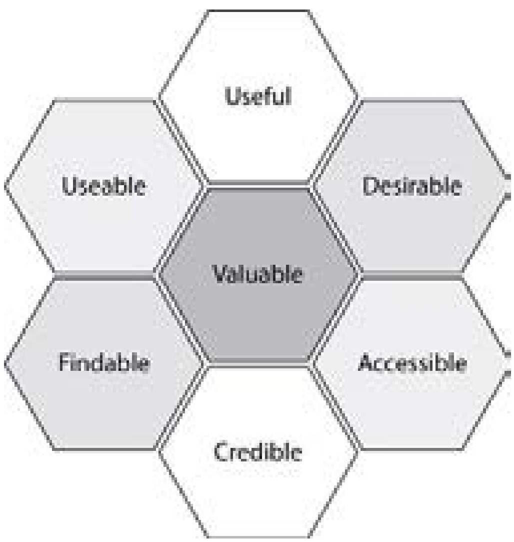



*Fig. 64:* Honeycomb Diagram by Peter Morville. Source: https://semanticstudios.com/user_experience_design/

95 Morville P. (2004), Last Access: 26.08.2019, https://semanticstudios.com/user_experience_design/

For each of the six columns – that refer globally to USEFUL, USABLE, DESIRABLE, FINDABLE, ACCESSIBLE and CREDIBLE sphere of user interaction – three positive adjectives and three negative adjective were chosen and they are positioned in an alternate way (in red the negative ones):
1. USEFUL column : Rewarding – Useless – Engaging – Absurd – Valuable – Indifferent
2. USABLE column : Familiar – Boring – Comprehensible – Complex – Intuitive – Tiring
3. DESIRABLE column : Elegant – Ugly – Ludic – Ordinary – Appealing – Inhibitory
4. FINDABLE column: Coherent – Non visible – Informative – Complex – Understandable – Difficult
5. ACCESSIBLE column: Relaxing – Intrusive – Comfortable – Limiting – Democratic – Expensive
6. CREDIBLE column: Reliable – Strange – Friendly – Aggressive – Ecological – Dangerous

"Valuable" is the adjecrive that is placed in the centre of the hexagons system and it represents the sum of all the other UX attributes around it, in fact the main aim of the honeycomb diagram is let designers to delineate a VALUABLE user experience for the final users.

### 5.3.3 Data analysis

The students' concepts about chromogenic materials applications focused on two big areas:

- The private level
- The private/public level

The concepts were divided in these areas of use to simplify the analysis and to focus on the user – product interaction. The objects in these field are characterized by the different ways people interact with them, the care aspect they have for them and consequently the durability characteristic they have. In fact, from the private sphere to the public one, the aspect of user's care for the product decreases – because if something has a specific and individual owner the level of care is higher but when things do not belong to a specific person, people's interest for it decreases and so the maintenance and care. From the private sphere to the public one, the level of comprehension of the product interface must increase because in the public sphere people have not so much time to spend for understanding something / how to use something / how the object works / how they must behave to use it. It is interesting to notice that mainly the students' concepts regard private fields of use and the public one was not addressed.

### 5.3.4 Final conclusions to sum up

The global students' opinion of this activity was positive because the workshop was useful to understand better the thesis topic, having some interesting clues about it.
The students chose private field in which proposing their applications concepts about chromogenic materials and this is reasonable in fact designing for the community can be harder and more difficult. Moreover, the students' previous background about chromogenic materials was a not so in-depth and detailed one, but the most known chromogenic materials are thermochromic, photochromic and hydrochromics. Then their knowledge about the thesis topic was to a medium-low level.
The thermochromic test they did - and that was previously described in chapter 5.2 - was very appreciated because it was fun and it was a useful tool to introduce the thesis topic related to surprise effect.

### 5.3.5 Extra notes

The initial step of the workshop activity consisted in trying different SFXC applications related to chromogenic materials samples that were useful to let the sixteen students understand what we were talking about if they never experienced similar products. The company SFXC was very functional and practical for my work because almost all the thermochromic inks and powder used to cover the samples for the thermochromic experiment were bought from this **company website**. [96]

96 Good Life Innovations Ltd., (2019), Last Access: 26.08.2019, https://www.sfxc.co.uk/

6

# DESIGN GUIDELINES

# 6. From the final out-comes to the design guidelines

## 6.1 Thermochromic test evaluation

After submitting the thermochromic test to 62 testers, the questions related to colour-shift materials and temperature aesthetic perception on visual point of view are faced. The warm and / or cold visual sensation is emphasize or reduced by colour-changing materials because of the transformation from the starting colour of the sample, during the test, to the final one. The testers answered questions related to the visual and tactile experience during the thermochromic experiment and in the first step they were asked to evaluate the colours temperature sensations of the samples before and after touching them. Different answers appeared due to the different colour perceptions of the testers. Then, analysing the diverse chromatic spheres linked to visual colour temperature, the testers evaluated five colour-shift configurations (in tab.3). The senses of  heat and warmth can be related to certain colours and shades, of course. with the main aim of creating a warm and / or cold aesthetics after the colour-shift.

| *(sample)* **STARTING COLOUR** → | **FINAL COLOUR** |
|---|---|
| *(A)* WARM CHROMATIC SPHERE **(orange)** | WARM CHROMATIC SPHERE **(yellow)** |
| *(B)* NEUTRAL COLOUR **(black)** | NEUTRAL COLOUR **(white)** |
| *(C)* COLD CHROMATIC SPHERE **(blue)** | COLD CHROMATIC SPHERE **(light-blue)** |
| *(D)* COLD CHROMATIC SPHERE **(green)** | WARM CHROMATIC SPHERE **(yellow)** |
| *(E)* WARM CHROMATIC SPHERE **(bordeaux)** | COLD CHROMATIC SPHERE **(light-blue)** |

***Table. 3:*** Thermochromic colour-shifts of the samples (from A to E). Personal Elaboration

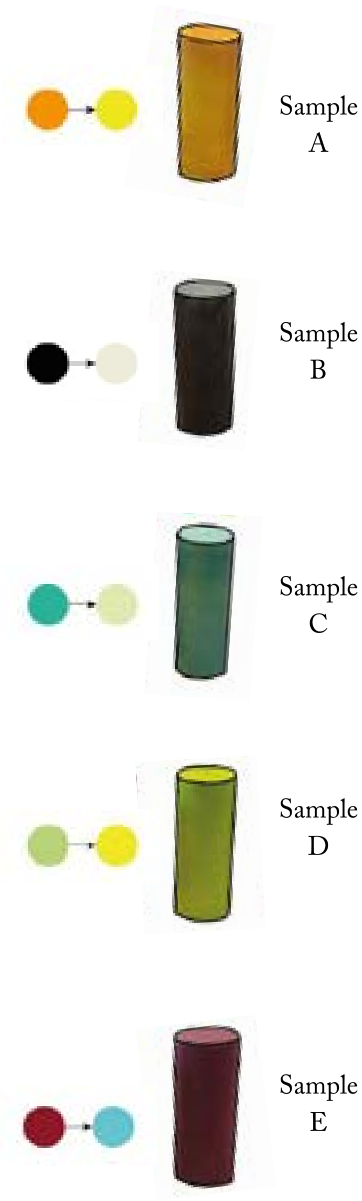



***Fig. 65:*** Graphic representation of the thermochromic samples in analysis. Personal elaboration at the Ecole des Mines (FR)

From warm-to-warm chromatic sphere - in the orange-to-yellow colour-shift - 30/62 testers perceived a warmer final colour of the sample (A) after touching it, taking in consideration that there were three negative visual feedbacks (testers who did not get the color-transformation after doing the tactile experience).

From black-to-white colour-change (sample B), 40 testers on 62 noted that the visual feedback became colder, considering four people who did not see the colour-transformation of the sample after touching it. Some testers did not perceive the white colour as final result because their hands were not so warm or they did not stay long waiting for the colour to change (after 3-5 minutes all the samples change their colours, even if the testers have low body temperatures).

From cold-to-cold colour-shift the test shows that for sample C (blue > light green), 32/62 testers perceived the sample colour as colder (with 2 negative visual feedbacks).

For the cold-to-warm colour-shift (sample D; green > yellow) the results are equal: on one hand, 29 testers thought that the colour transformation led to colder visual perception, and on the other hand 29 testers went for the warmer chromatic shift, considering four negative visual feedback. In this case the starting and final colour were very similar and the contrasting colour combination very poor: this can be the reason why the testers' answers are identical here (because the starting colour and the final one are perceived almost the same).

The last sample (E) shows the warm-to-cold colour-shift and it demonstrates that testers perceived the final colour (light-blue) as colder than before (bordeaux is the starting colour) considering now seven negative feedbacks on visual point of view because of the higher activation temperature and the use of thermochromic powder instead of thermochromic ink.

Then, in conclusion, a change in the starting perception of warm / cold colour temperature is possible and it is also possible to enhance both sensations, chosing the proper starting and final colours of the samples.

### 6.1.1 Colour-shift rapidity vs Surprise effect

**The colour-shift rapidity is really appreciated: the faster the visual feedback is the better is the UX experience for the tester.** In fact, after the first visual and tactile experience with the first thermochromic sample, the tester expects the same colour-changing rapidity and he is surprised if the colour-shift is faster. On the contrary, **if the rapidity dicreases from a sample to the other, the negative visual feedback creates frustration in the partecipant.** Moreover, the worst the visual and tactile feedbacks are, the more appreciated the hot water-samples interaction is, at the end of the experiment (this fact is demonstrates by sample E).
For this reasons, **the most surprising samples evaluated in the thermochromic test prepared, are sample A (orange > yellow; Activation temperature around 27°C) and sample E (bordeaux > lightblue, Activation temperature around 31°C).** Sample A was appreciated because the colour-shift was rapid and also because it was the first sample that the testers tried and experienced. Sample E was even more surprising than sample A, because the tactile experience produced a negative feedback for several testers creating dissapointment in them. But, with the water experience that followed, the colour-shift was evident and the colours of the sample were vivid and powerful. Furthermore, the colours in this last case were very contrasting colours belonging to opposite chromatic spheres (bordeaux-warm > lightblue-cold) and the result was a more lively surprise because of the very eye-catching and interesting colour-shift.
**The less surprising samples were sample B (black > white; Activation temperature around 27°C) and sample D ( lightgreen > yellow; Activation time around 31°C), due to the fact that the first one was a non-coloured shift because black and white are neutral colours, as a common and very frequent idea.** In theory, infact, black represents the absence of colour - in physics, a black body is a perfect absorber of light - and white is the sum of all the colours of the visible spectrum. Sample D shift was not so interesting on visual point of view because the starting colour and the final one were very similar and the transformation from one to another did not create a contrasting colour combination. The surprise effect decresed of course from the first sample A to the final sample E because

after the first one, the testers expected all same responses from the thermochromic samples and they already knew the physical dynamics and changes of the thermochromic materials. But due to the fact that the negative feedback increases from sample A to sample E, the tactile and visual experience gets worst too. For this reason, especially with sample D and sample E that have the worst responses in terms of colour-shift and rapidity, sample E had the best results regarding the surprise effect during the hot water experience in the final step of the thermochromic experiment.

The thermochromic experiment shows that, in a scale from 1 to 4 (in which 1 is very slow and 4 very fast) the colour-shift rapidity:
- of sample A (orange > yellow) was considered very fast (level 4) by 40/62 testers;
- of sample B (black to white) was considered very fast (level 4) by 27 testers and fast (level 3) by 23 testers;
- of sample C (sea blue to light green) was judged fast (level 3) by 26 testers;
- of sample D (green to yellow) was considered fast (level 3) by 15 testers, slow (level 2) by 16 testers and very slow (level 1) by 14 testers;
- of sample E (bordeaux to light blue) was judged very slow (level 1) by 40 testers.

**These results are in accordance with the different activation temperatures of the samples, with testers' negative feedbacks that increased from sample A (with lower activation temperature around 27°C) to sample E (with higher activation temperature around 31°C and more).**
Not considering the first sample (A) that was very surprising because it was the first one experienced by the participants, the surprise increase very much from sample A to sample E after the water-samples interactions. In fact sample E, that shows the worst tactile feedbacks linked to very slow colour-shift rapidity during the tactile experience, represents the most surprising sample at all during the final warm water-specimen interaction. According to the results then, the slow colour-shift rapidity during the tactile experience is correlated to higher surprise effect in the end of the test because the testers' expectations got higher. Moreover, sample E presented

a very contrasting colours combination compared to sample D for instance, whose colour-shift rapidity was considered average slow but with no very evident differences between the starting colour and the final one. For this reason it was the least surprising sample at all. In fact in addiction to the negative feedback, it presents also a non-satisfied surprise effect.

### 6.1.2 Colour-shift rapidity vs Good and bad feedbacks for UX

The rapid visual feedback is enormously appreciated by testers during the thermochromic experiment and after the first user experience with the sample A they expected a similar colour-shift rapidity otherwise they asked the reason why the other sample did not change so fast and did not change colour at all (as the sample E for several testers). The negative tactile feedback was considered with disappointment because they could not see the colour transformation and they probably though they did not do the test correctly or their hands had something wrong. The negative feedback with no visual reaction is not well understood by testers and they continue the experiment with some doubts about the specific sample/s with non-coloured effects. In theory, **the negative feedback occurs when some functions of the output of a system, process or mechanism is fed back in a manner that tends to reduce the fluctuation in the output - in this case colour-change - whether caused by changes in the input or by other disturbances**.[97]
In conclusion, the good combination between rapid visual feedbacks - to be better undestood by potential users - and colour-shifts choices is going to be described in the final design guidelines.

97 Your Dictionary. (2018); Last access: 27.08.2019; https://examples.yourdictionary.com/examples-of-negative-feedback.html

## 6.2 Design guidelines for projecting surprise using thermochromic and hydrochromic material

### 6.2.1 The purpose of the design guidelines

The design guidelines could be used as a tool for designing surprise using thermochromic materials to enhance UX and they allow the designer to focus on special key points before starting the design project and also while doing it. The modality through which the surprise emotion could be triggered and amplified, the external context that must be created and the product characteristics that could activate it, are discussed. Starting from some clues obtained from the thermochromic experiment, these surprise characteristics are structured according to the six attributes of the honeycomb diagram by Peter Morville.

Projecting the proper combination of both visual and tactile experience through thermochromic materials could drive next designers' projects who desire to delineate a surprising and smart product.

The special intent of the design guidelines could make the chromogenic materials overview more complete and understandable. To support the thesis position and the intent of these design guidelines a research was made related to existing thermochromic and hydrochromic materials and products that validate the smart directive that are going to be suggested. They are used as case studies and they also comprehend concepts not already on the market.

### 6.2.2 Some considerations for projecting the design guidelines

The ideal conditions to maximize the surprise effect in design thermochomic and hydrochromic products and which the designer must pay attetion on, are:

- The colour-shift rapidity of the material could lead to a good UX or a negative one in case the visual feedback is prevented by external factor, an improper way of use the material, etc;

- the colour- shift modality: characterized by irreversible or reversible colour- shifts;

- the colour shift associated to a correct or uncorrect product use: this condition increase significance and value to the product and to the effect of surprise due to te extra intrinsic meaning embedded in the smart material;

- the very different chromatic spheres between the starting colour and the final one, both in terms of tints and shades and colours sensations of warmth and coldness. This point can be explained by the fact that **warm colours like red, orange, and yellow are stimulating while cool colours such as blue and green are calming.**[98] The emotional and psychological aspects of colours can be determined scientifically. For example, the colour fading effect to clearer tints is very appreciated by testers;

- The activation temperature of the smart material must be chosen carefully and to create a valuable tactile UX it must be around 27°C otherwise the colour-shift takes more time to appear. The user's frustration - linked to possible negative visual feedbacks - begins after 10 / 15 seconds after the first interaction with the thermochromic materials: if nothing changes in

98 Ferrara M., & Bengisu M. (2014). Materials that change colour smart materials, intelligent design. p. 82; Cham: Springer.

the smart object during this range of time the surprise effect enourmously decreases, even if the colours will appear later.

- There is not a big correlation between the users' personal colours preferences and the effect of surprise: this fact represents a subjective aspect of the analysis that cannot create important design rules. But it is important to underline that the neutral colours that theoretically are white, grey and black give very lower surprise feedbacks compared to the other colours in the colours wheel.

### 6.2.3 Design Guidelines and case studies

The eight design guidelines are supported by several case studies and they are structured according to the six main points of the honeycomb diagram (*USEABLE, USEFUL, DESIRABLE, FINDABLE, CREDIBLE, ACCESSIBLE*). Each point is described individually and reinforced by one-to-four case studies in order to give a global and overall view of the subject, and to deepen and to complete the explanation with real objects references.
Moreover, to better organize the design directions to make them more clear to use, it is important to resume the description of the *emotion* of surprise that can be explained through the Appraisal Process Approach[99] that is based on the cognitive theory of emotions. In the scheme below (fig.66) - that follows the previous approach - the *stimulus* is represented by the product and the *interest* relates to particular user's needs to accomplish a goal and / or avoid damages. Starting from these two main points regarded the product UX, the user's *appraisal* will follow. It represents a personal evaluation that the user unintentionally performs toward the product, after coming into contact with it and that refers to the symbolic attributions and meanings that the product embedded for the user. In fact, the appraisal is due to user's personal interests. The evaluation, already defined as appraisal, does not refer to the design product in itself but it is linked to the - negative or positive - meaning that the user attributes to it.
From the combination of the three aspects described graphycally in the following image (fig.66), the user's emotive response follows.
The model proposed here is based on a psychological vision of product emotions. In fact, it represents the cognitive mechanism that occurs in correspondence of user's observation, use, ownership, his imagination of a design product and his

99 See paragraph 3.2

consequent emotional response.
This scheme is important in this discussion to describe the more recent hypotheis that was made in product emotions field and that follows the two main studies by Jordan and Norman previously described. [100]

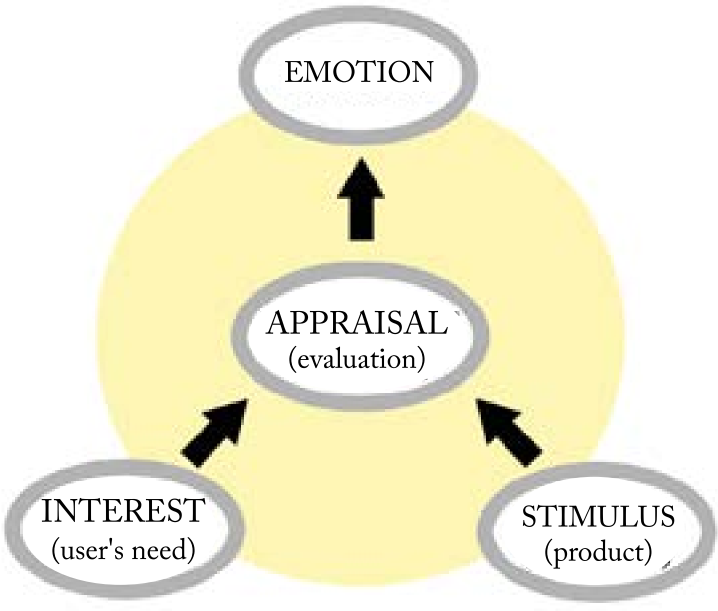



***Fig. 66:*** Desmet and Hekkert' scheme related to the appraisal process approach.

Source: Pieter M. A. Desmet, (2003)

A multi-layered model of product emotions

To give the reader a final and global idea of all the case studies chosen and arranged, according to the honeycomb diagram main principles, a conclusive table (table 5) was created at the end of the case studies description, to summarize the principal characteristics of the chromogenic examples selected. A special focus was made on the surprise effect of each case study and its specific property of UX (e.g. usability, usefulness, etc).

100See chapter 3: Pleasure approach and Process Level approach

## *USEABLE*

The usability of an object refers to its semplicity to be understood and to be used by the final user. This term describes the ease of access or use of a product.

The designer must focus on the **modality of user-product interaction** during all the design process, trying to project it as more **personal and unique** as possible for the user in order to be more appreciated. The way the end user will interact with the smart object represents an important design keypoint because it could affect the conclusive costumers' response after the whole product experience and also his - positive - memories of the past user experience. The surprise effect lies in the uniqueness of the thermochromic material - the colour-shift - and in the **personal usability of the smart object** that is established with the user. For example, the thermochromic material in ***case study #3*** is exploited to communicate the character of the smart body cream container. The humanized reaction of the material - that "blushes" like a human being - in this case create a very unique connections with the user. The ***case study #1*** for example is represented by a smart table that is intended to surprise the end user but also to extend the user-product interacton over time.

The designer who wants to project surprise through thermochromics should study the modality of interaction between the object and the end user that includes the **choice of the product interface**, the way it will appear to the user, **what are the parts of the smart object that will be touched by the end user and in which there will be the physical contact, merging the user into the product** (the ***case studies #1 and #2*** represent two items that are entirely covered with thermosensitive materials because the user's interaction could occur on the whole surface of the object).

If **the colour-shift is permanent or last for a long time**, the UX is more appreciated by the end user, in fact the presence of the coloured mark on the material surface witnesses the lived experience. This evaluation was taken from the thermochromic experiment previously described. On the contrary, the very fast colour-shift to the starting colour is not very appreciated by the testers: the colour-shift traces on the material have a more emotive value if they last longer (as in ***case study #1 and #2***).

The designer needs to focus on the **controllability of the thermochromic material**: the user should be able to control his own interaction with the smart product. Thermochromic inks and powders allow the users to leave their own **fingerprints** on the objects material and the end users could control the colour-changes due to their own **body temperature** and **hands pressure** on the surface of the product, as in ***case studies #1, #2, #3*** in which the coloured marks bring extra meaning to the design products through a more distinctive and unique UX because the end user leaves its own imprints on the material, creating something **unrepeatable and intimate**. In fact, the materials response is different for each person. The designer should focus on the **activation and relaxation time** of the smart material to project the UX, also adapting the reversibility or irreversibility of the smart material to the specific use of the product and its use over time (e.g. if the product is designed for an extended period of use, the designer could make its surface trasformable over time, consumed by the prolonged use in an irreversible way).

***Fig. 67:*** Case study n.1: Linger a little longe by J. Watson, 2011.
Image taken from http://jaywatsondesign.com/index.php/portfolio_page/linger-a-little-longer/
***Fig. 68:*** Case study n.2: Heat Seat by J. Mayer, 2002. Developed for Archilab 2001. Collection of SF MoMA, San Francisco, USA courtesy mullerdechiara, Berlin.
Image taken from http://www.jmayerh.de/47-0-Heat-Seat.html
***Fig. 69:*** Case study n.3: Care product packaging by N. Stas, 2015
Image taken from http://it.materialconnexion.com/naked-by-neretin-stas-un-progetto-di-packaging-termosensibile/. Material Connexion Italia


## CASE NUMBER
#1

## CONCEPT NAME
Linger a Little Longer by Jay Watson

## YEAR
2011

## CONCEPT DESCRIPTION

After the UX with the smart table, the user will find out its real and **hidden nature** and the effect of surprise is immediately generated. The designer intended to allow the user to get closer to the product and **extend the user-product interaction**. The intention of the user can be also to **repeat the action**, after the first interaction. The **human trace** after the physical product experience appears in a visible and **reversible** way. The user's fingerprint are not permanent but they describe how the product experience changes due to the user' actions and movements so that the user feels **in control** of the material. The surprise effect starts only after a brief time of use and a very amusing reaction will follow. In fact, the fingerprint creates a very **personal product experience** that does not end after the first use.

| KEYPOINTS | Hidden nature; extended and personal user-product interaction; Human trace and fingerprints; user's control of the material |
| --- | --- |


## CASE NUMBER
#2

## CONCEPT NAME
Heat Seat
by J. Mayer

## YEAR
2001 - 2002

## CONCEPT DESCRIPTION

The surprising and new idea proposed with Heat Seat is to **merge the viewer into the product**, using warm colours such as reddish tints and shades, to **increase the sense of warmth**. Heat Seat develops the personal UX in a powerful way that is based on surprise effect and unexpected material reactions, by introducing thermosensitive coating as interactive paintings where the user, creating a temperature **body imprint** by touching, melts into the overall product design. The keypoint is to make the **whole object surface reacting** so that the aestheticsof the smart product changes due to **user's control**.

KEYPOINTS

Merging the user into the product; Sense of warmth; Personal UX; Body imprint; ; User's control


## CASE NUMBER
#3

## CONCEPT NAME
Care product packaging by Neretin Stas

## YEAR
2015

## CONCEPT DESCRIPTION

The smart packaging reacts to human body temperature and it is characterized by **the link between a personal use of an everyday product and human emotion of surprise**. The interactive package behaves as a human being: it gets embaracced after being touched. "Be gentle with this package, it is very shy" are the designer's own words according to its special properties. When touched, the Naked packages timidly glows right where the contact was generated in a reversible modality, recreating the human skin characteristics. **The container reflects the character** of what its content is used for and the end user will be astonished because the product acts like **alive matter**.

KEYPOINTS

Everyday product; Surprise effect; Product character; Alive matter

HONEYCOMB DIAGRAM PRINCIPLE

USEABILITY

DEFINITION

*Semplicity to be understood and to be used by the final user. This term describes the ease of use of a product.*

DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS)

1.
**The designer should focus on the uniqueness and personal user-product interaction that must be as much unrepeatable and intimate as possible:**
- Focus on the smart object interface; its number and type of parts that will be touch by the end user; the interactive product could behave as a human being (attribute human characteristics to the product); letting the user merge into the smart product;

- The alive smart material properties could reflect the character of the design product and its function.

- Think about the period of use of the product (e.g. extended period of use if in case of an everyday object)

2.

**Focus on the contrallibility of the smart object** (hand pressure, activation and relaxation time and temperature).

- The long lasting mark is more appreciated in terms of surprise

CASE STUDIES

#1 #2 #3

#1 #2

KEYWORD PHRASES

Personal user-product interaction;
User's fingerprint and body temperature;
Merging the user into the product
The material should reflect the product character

***USEFUL***

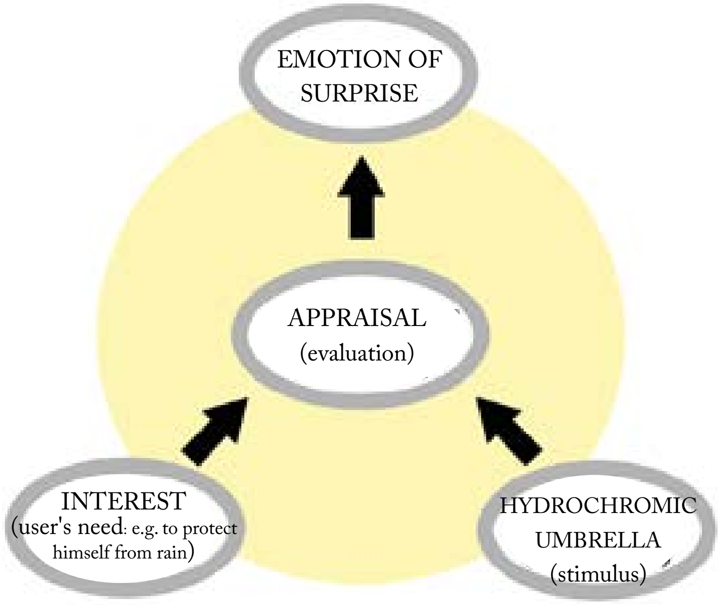



***Fig. 70:*** A practical Example of use of Desmet and Hekkert' scheme related to the appraisal process approach. Source: Personal Rielaboration

A design product is useful if it fulfills properly the specific task/s which it was made for and if it answer to a particular need.

To better describe this subject linked to surprise effect, **Desmet and Hekkert' scheme**[101] is adapted to a practical example to be better understood. The user's *need* can be represented by the necessity of protecting himself from rain and the *product* is characterized by an hydrochromic umbrella for instance (useful to solve the weather problem - ***case study #5***). These two point together allow the user to perform - also unconsciously - an *evaluation* of the product experience that, due to the external context and factors, can be positive or negative for the end user and that follow an initial emotion of surprise.
The surprise effect is not valuable alone but it must be considered with other relevant elements - like **the familiarity of the object for the user, the user's mood during the action**, etc. In this example the hydrochromic *umbrella-stimulus* is central because it is related to **user's interests** that are contextualized in the real interaction.

The designer who wants to project surprise through thermochromics needs to pay attention to the **context of use**, that is important to understand the product experience and the emotion of surprise. The effect of surprise is going to be described and summarized in different environments (public, domestic, private, scholastic, hospital and commercial ones)

101 See fig. 66 pag 109

that are related to the test prepared by **Ludden et al**[102].

A surprising product experience has a positive impact in a **public context** if it is a waiting place for instance, in which the presence of an unusual smart object represents an entertainment source that relieves people from boredom (***case studies #4 and #5***). The colour-changing bench (***#4***) exploits the thermosensitive material which it is made of, to create playful chromatic changes after being touched. The user is then driven to deepen the knowledge of the material and to find out what happen next to the colourful bench during the use and in this sense he does not get bored.

The unusual property of the smart umbrella (***#5***) represents an interesting way t**o break up the monotony of everyday** life characterized by boredom (e.g. waiting the train or the bus) thanks to the alive response of the hydrochromic material which it is made of.

The public context could be also represented by **commercial environments dedicated to products sale** in which the user's experience is aimed to purchase, the presence of surprising smart product risks of being not so appreciated by costumers due to less time and the absence of their concentration during the shopping activity. On the contrary, during **commercial activities more focused on the costumers**, the surprise effect has a positive valence because it encourages user's involvement and amusement not only as a costumer but also as a human being, with the time for **maximising his memories** related to previous similar UXs.

For the **domestic context** the opinions are discordant because the smart objects used in this context are affected by the **one-time emotion on** one side, and the possibility **to socialize through surprising experience** on the other side (***case studies #6***). Depending on the social context of use, the designer should ampify the first surprising UX - one time emotion - to leave in the user a **strong and lasting memory of the surprising event**. The one-time emotion effect could be very strong ccompared to the next ones because after the first user-product interaction, the user gets used to the hidden property of the thermochromic materials. For this reason **the designer should focus on the aesthetic or functional aspects of the smart object to trigger the emotional system of the end user**. The thermochromic mug - ***case study #6*** - modify its colour due to the different temperature of the liquid inside and so it communicates an extra meaning to the end user. Moreover, the thermochromic mugs are designed to surprise at first but they also represent a valid tool to socialize with other people and for this reason they increase their social values over time.

The smart umbrella - in ***case study #5*** - could improve the user's mood while raining so it has an emotional content.

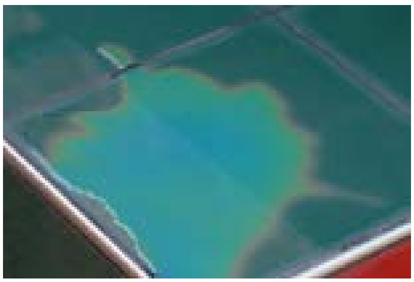
### *DESIRABLE*

102Ludden, G. D. S., Schifferstein, H. N. J., & Hekkert, P. (2006), Sensory incongruity: comparing vision to touch, audition and olfaction in The Fifth International Conference on Design and Emotion, September 27-29, Goteborg, Sweden. Retrieved from https://pure.tudelft.nl/portal/en/publications/sensory-incongruity-comparing-vision-to-touch-audition-and-olfaction(310191f9-4656-4bc5-8278-1018bdc4669a).html

***Fig. 71:*** Case study n.6: Colour-changing bench by S. Falls, 2015
Image taken from https://www.movingcolor.net/portfolio-items/aurora-public-art-bench-5/. Author of the image: Moving Colour Studio

***Fig. 72:*** Case study n.7: SquidLondon Umbrella, 2008
Image taken from http://www.squidlondon.com/

***Fig. 73:*** Case study n. 9: Thermo Mug by J. Rudbeck, 2015
Image taken from https://www.designboom.com/project/thermochromic-2/. Author of the image: Jacob Rudbeck. 2007




## CASE NUMBER

#4

## CONCEPT NAME

Color-Changing Bench
by Sam Falls

## YEAR

2015

## CONCEPT DESCRIPTION

The colour-changing bench is very **entertaining** while waiting in public places and it could be fun to use for children. Its surprising usefulness lies in the amusement it creates. The end user will experience a surprising usability that does not end over time. For this reason and for the reversible modality of colour-shift, the final user will **keep to interact with the object for a while**, to find out what are the chromatic changes on the surface. The starting colour **fades and becomes clearer** and this fact emphasize the final surprise emotion.

| KEYPOINTS | Entertaining; Public place; Surprising usability over time; Reversible modality of colour-shift; Fades |
|---|---|


## CASE NUMBER
#5

## CONCEPT NAME
SquidLondon Umbrella

## YEAR
2008

## CONCEPT DESCRIPTION

The thermochromic material which the smart umbrella is made of, shifts colour in the rain due to its hydrochromic nature. The smart properties of the umbrella express an **emotional content**, specially of surprise. The umbrella designers' inspiration was the **colourful user's interaction** with the rain, based on Jackson Pollock's art. The aim is to surprise users during rainy days **to improve their mood**. The chromatic shift is totally unexpected and it helps to reverse a not so pleasant everyday situation to a very funny and surprising one.

| KEYPOINTS | Improving user's mood; Fullfillment of user's need; Emotional content; Colourful user-product interaction |
|---|---|


## CASE NUMBER
#6

## CONCEPT NAME
Thermo Mug by Jacob Rudbeck from Denmark

## YEAR
2015

## CONCEPT DESCRIPTION

The smart mug helps the user to become aware of the liquid temperature inside. This fact can be useful for safety reasons (e.g. not to burn his own hands) and it could have **aesthetic purposes** due to the chromatic shifts of the material surface. The mug could be **personalized with the user's pictures and this fact leads to a more personal and affective product experience over time**. This concept avoids annoying situations in which the user is obliged to wait for something (e.g. coffee breaks at work, etc) and it makes them more fun.

| KEYPOINTS | Aesthetic purposes; Personalization; Affective user-product experience |
|---|---|

| HONEYCOMB DIAGRAM PRINCIPLE | USEFULNESS |
| --- | --- |
| DEFINITION | *Fulfilling properly the specific task/s which it was made for and if it answer to a particular need.* |
| DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS) | 3. **Focus on the context of use:**<br>a. **PUBLIC**:<br>- To break up the monotony of everyday life (while waiting e.g.) through the smart properties of the thermochromic material;<br>- To avoid stressful and chaotic situations in which the user is under pressure (e.g. commercial contexts) and he could not understand the smart properties of the material;<br>b. **DOMESTIC**:<br>- focus on one-time emotion and socialization originated from the smart object (it increases its value over time not losing user's interest)<br>- The designer should focus on aesthetic / functional aspects of smart objects to trigger user's emotional system (e.g. the smart object personalization leads to a more personal and affective product experience over time) |
| CASE STUDIES | #4 #5 (PUBLIC); #6 (DOMESTIC) |
| KEYWORD PHRASES | Context of use; One-time emotion; Socialization; User's memory of the past UX; Aesthetic and functional aspects; Emotional system; Affective product-experience |

A product is desirable if it triggers emotions in the end user that can be related to its aesthetic aspects, user' personal interest, curiosity for its functions, shape, colours.

The strategy for activating curiosity and surprise in a design object can be characterized by the use of thermosensitive properties to rouse fun and amusement. The **ironic elements** of a product do not stop being perceived over time, they only reduce their impact. For example, the slightly odd shapes or smart details of the objects will **attract the attention of the user and invite him to interact with them** (the thermosensitive finishes of the smart dress in the ***case study #9***).

Another strategy for designing surprise and that could also be adopted in chromogenic materials field, is represented by the so called **"opposite techniques"**[103]. They refer to the fact that the main user's expectations are linked to everyday objects in his daily life. These expectations are associated to **simple products** that he usually uses and which he has a high level of certainty for. If the design object will **diregards these certainties**, the user's emotive impact will be bigger (as it is verified by ***case studies #7 and #8***). To create a relevant surprise, and to avoid being misleading at first, the "opposites method "centres on the essential qualities of the object (coffee tables in ***case study #7***, or tablecloth ***in case study #8***). The first quality of any coffee table (or tablecloth) is that it supports objects, especially food, avoiding their pouring over. The coffee tables and the tablecloths must also be cleaned and ordered to give a pleasant idea of sociality and sharing. In fact, these two case studies represent products that are used with other people in social contexts, in which the politeness is central to encourage socialization. This quality is essential for the idea of "coffee tables" and "tablecloth" in itself: a coffee table which does not seem cleaned gives a bad impression on the possible users. Therefore this property in the coffee table could not be subverted. Using the opposite connotation (dirty for instance) of the previous coffee table characteristic, the amusement is guaranteed and the surprise effect could easily arise from that. Actully, both the coffee table and the tablecloth Underfull become more beautiful if they get dirty (**typically the filth is associated to the ideas of neglect, carelessness, innacuracy and they are not positive connotations, but with the opposite techniques they are overturned**). Underfull by Kristine Bjaadal (***case study #8***) is a tablecloth that likes to get dirty and this fact creates stories and can contribute in giving the tablecloth sentimental value – important in a society where we seem to have an increasingly superficial relation to the objects we surround ourselves with.

This funny characteristics of surprising objects elicit an **emotion of interest** in the end user: it gives emotional stimuli after users' evaluation of products that require a deeper exploration and that **awaken questions in the final user through his involvement**. In conclusion, the

103 Grimaldi S. (2008), The Ta-Da Series - Presentation of a methodology and its use in generating a series of surprising designs, Anglia Ruskin University - UK. Retrieved from: https://www.academia.edu/545091/The_Ta-Da_Series_ _Presentation_of_a_methodology_and_its_use_in_generating_a_series_of_surprising_designs

emotion of interest is linked to users' enjoyment and delight, regarding aesthetich properties of the smart product.

***Fig. 74:*** Case study n.10: Impolite coffee tables by S. Grimaldi, 2015
Image taken from https://www.coroflot.com/silvia_grimaldi/portfolio1. Author of the image: Silvia Grimaldi

***Fig. 75:*** Case study n.11: Underfull by K. Bjaadal, 2009
Image taken from https://www.kristinebjaadal.no/portfolio/underfull/. Uthor of the image: Kristine Bjaadal

***Fig. 76:*** Case study n.12: Rainforest Collection by A. Winters, 2007
Image taken from https://www.rainbowwinters.com/. Author of the image: Cereinyn Ord

*FINDABLE*


**CASE NUMBER**
#7

**CONCEPT NAME**
Impolite

Coffee Tables by Silvia Grimaldi

**YEAR**
2015

**CONCEPT DESCRIPTION**

**Only the dirt and liquid filth let these smart coffee tables be more beautiful,** revealing the flowery pattern beneath. If spilling some liquids on them represents an action that makes the tables more appealing, **the user is forced to repeat this movement, reinforcing the sense of impoliteness**, since spilling coffee on a table is something that people usually excuse themselves for. In this way the abuse of the coffee table is turned into a positive addition **subverting the social rules and it creates fun**. If the user tries to insert the smallest table into the other ones, he could not succed in doing it: they are not really thought for being fixed together. This represents the second surprise: it makes the **discovery more surprising and satisfying**.

KEYPOINTS — Subverting the social rules; Creation of fun; Discovery


## CASE NUMBER
#8

## CONCEPT NAME
Underfull by Kristine Bjaadal

## YEAR
2009

## CONCEPT DESCRIPTION

In this design product a **hidden pattern** shows when wet. Sooner or later someone is bound to spill, but where this person usually feels embarrassed, he will now feel fortunate. **An everyday negative situation is turned into a positive experience, according to the Opposite Techniques**. Some stains (e.g. red wine) are hard to clean and might leave colour traces also after washing. But since these traces will be formed as figures, the tablecloth will not look stained. Then, the end user is stimulated to increase his use of the tablecloth.

| KEYPOINTS | Turning an usual negative situation into a positive one; Opposite Techniques |
|---|---|


## CASE NUMBER
#9

## CONCEPT NAME
Rainforest collection

by Amy Winters

## YEAR
2007

## CONCEPT DESCRIPTION

This smart dress represents is slightly detached from the previous two case studies because it has mainly **aesthetic purposes** due to the wonderful tints and shades created after the water interaction. **Its decorative and ornamental aims** are based on **vivid colour-shifts and not the black to white ones** (that are not usually exploited due to the less surprising effect that they stimulate in the final user). The water interaction was very appreciated due to its **ironic connotation** and the lively colours that appear after the input.

| KEYPOINTS | Aesthetic purposes; Vivid colour-shifts; Ironic cconnotations |
|---|---|

| | |
|---|---|
| HONEYCOMB DIAGRAM PRINCIPLE | DESIRABLE |
| DEFINITION | *A product is desirable if it triggers emotions in the end user that can be related to its aesthetic aspects, user' personal interest, curiosity for its functions, shape, colours.* |
| DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS) | 4. **Focus on the strategy for activating curiosity and interest in the final user through:** a. The combination of vivid and intense colour-shifts and odd product shapes (*case study #9*); b. The use of the smart material to create fun for the end users to stimulate his interest and to create a globally positive UX; c. Disregarding user's certainties related to everyday and simple object to emphasize his final emotion of surprise using thermosensitive materials (**Opposite Techniques**: e.g. a stain becomes a beautiful pattern) |
| CASE STUDIES | a. → #9; b. → From #7 to #9; c. → #7, #8 |
| KEYWORD PHRASES | Curiosity and interest in the final user;<br>Disregarding certainties;<br>Emotion of surprise; Opposite Techniques |

The findability of an object describes the ease with which information related to its function, usability, etc can be found by a potential user. To be findable, a design product needs to be as clear as possible, showing all the information regarding the way it can be used, how it works and therefore its functionality.

The thermochromic and hydrochromic materials answer as alive matter without using verbal language in an **immediate and easy way**. In fact, they allow the designers to communicate through the materials surface of the product.

**Designers should focus on the timing of communicating the specific message and meaning driven by the design product.** It is essential in storytelling and in all sorts of narrative media and it is integral in surprise. The smart materials are surprising during the first UX because they are unexpected, characterized by uncommon product features. On the contrary, during a **long period of use**, the surprise effect is experienced gradually because the materials reveals its own hidden properties over time and when the user finally perceives their changes, his emotive reaction does not end but at this point the user's curiosity for the next material trasformations starts. To create the right sense of timing it is important that several things happen in sequence during the interaction with the objects. If the object feedback is not misexpected but it takes a lot to show up, the final result is represented by a very frustrating product experience due to the **negative visual feedback** and most of the time, the end user does not comprehend entirely what are the relevant characteristics of the smart product.

Then, for designing a very **intuitive user-product experience** using chromogenic materials, the colour-shifts could increase the functionality of the final product if they are associated to **correct and uncorrect use of the object** and for this reason, they must be very visible and the colours chosen can be linked to product functionalities - employing the psychology of colours method and principles. This condition **increases significance and value to the product and to the effect of surprise due to te extra intrinsic meaning embedded in the material** and in the colour-shift chosen (as in ***case study #11*** in which the colour of the working radiator is red and it represents the heating up of the room temperature).

The keypoint on which the designer could focus on is the possibility **to adapt the smart material properties to the external environment**. The weather for example could improve the findability of the hydrochromic map - in the ***case study #12*** - and it help the user to understand how the smart product really works. In fact, the map suggests to the end user how to spend time in the city during rainy days. Then, the external conditions such as the rain represent valid tools for communicating a message throught the smart material and making it more informative for the end user.
The main features of the object - linked to its way of use and its functionality - must be

locatable, maybe underlined by vivid and intense colour-shifts (as in ***case studies #11 and #12***) or by fading colour effects (***case study #10***).

***Fig. 77:*** Case study n.17: Holo Lamp by P. Domanska, 2012
Image taken by https://www.dailytonic.com/holo-pendant-lamp-by-patrycja-domanska-at/. Author of the image: Patrycja Domanska

***Fig. 78:*** Case study n.18: Radiator by D. Radaelli, 2007
Image taken by http://www.davideradaelli.com/Industrial_projects/Heat's%20Colour.htm. Author of the image: Davide Radaelli

***Fig. 79:*** Case study n.20: Thermo-colour map by C. Hempleman, 2015
Image taken from https://www.designboom.com/technology/thermo-color-map-camilla-hemplman-07-28-2015/

***CREDIBLE***


## CASE NUMBER
#10

## CONCEPT NAME
Holo Lamp by Patrycja Domanska

## YEAR
2012

## CONCEPT DESCRIPTION

The small pendant lamp made of aluminum by metal spinning and coated with a special thermosensitive paint, which changes color from turquoise to white when reaching 31 degrees, creates amusing and funny plays of light. The **fading colour effect** emphasizes the starting emotion of surprise in the user. **The usability information is well presented due to the visible colour-shift of the material surface**. In this way, the user recognizes immediately that the colour-change of the external lamp corresponds to an increse of the light-bulb temperature.

KEYPOINTS: Fading colour effect; Usability information; Visible colour-shift


## CASE NUMBER
#11

## CONCEPT NAME
Radiator by D. Radaelli from Italy

## YEAR
2007

## CONCEPT DESCRIPTION

This smart radiator is a "findable" design product because **the colour-shift is used to communicate an information that is central for its functionality and usability**. Red is associated to the heating condition of the working radiator, transmitting a sense of warmth on visual level to the users. The thermosensitive properties of the object are characterized by a colour-shift from grey to red. This chromatic choice - based on the **transformation from a neutral colour to a more vivid one** - emphasize the final user's effect of surprise. The information is visible and understandable information thanks to human natural association between colours and temperature.

KEYPOINTS: Communicating information; Neutral colours to lively one


## CASE NUMBER
#12

## CONCEPT NAME
Thermo-colour map by C. Hempleman

## YEAR
2015

## CONCEPT DESCRIPTION

The hand held activated map is based on the designer's home city. The use of the thermosensitive inks and tyvek fabric - that activate at different temperatures - creates surprise in the end user, thanks to the fact that these materials reveale several layers of hand illustrated attractions, showing the best **findable places** to visit depending on the **weather** (e.g. museums while raining). Then, the end users establish a sort of relationship with the designer without really knowing her. **The different colour-shifts suggest diverse places to visit and they are diverse for each range of temperature**: between 25 and 30°C a pink colour will appear, at 15°C and below the light blue city routes become evident and at **rain activation** the colour chosen is blue.

| | |
|---|---|
| KEYPOINTS | Findable places; Different colour-shifts; Rain activation |

HONEYCOMB DIAGRAM PRINCIPLE

FINDABILITY

DEFINITION

*To be findable, a design product needs to be as clear as possible, showing all the information regarding the way it can be used, how it works and therefore its functionality.*

DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS)

5.

Communicating the colour-shift and the hidden nature of the smart material in an **immediate and easy way ( avoiding negative visual feedbacks** of smart material properties):

a. For designing a surprising **user-product experience** using chromogenic materials, the colour-shifts could increase the functionality of the final product if they are associated to **correct and uncorrect use of the object;**

b. The designer should focus on the possibility **to adapt the external environment conditions as a tool for making the smart material more informative** (e.g. rain)

CASE STUDIES

#10 #11 #12

KEYWORD PHRASES

Communicating in an immediate and easy way;
Avoiding negative feedbacks;
Intuitive user-product interaction; External weather conditions

An object is credible if the final users can rely on it during their first product experience and also over time, and if they are encouraged to believe in what the product tells them due to its simply understandable functionality.

The product experience must be **reliable** especially according to particular design fields, as the safety one for instance, in which the product performance needs to be optimal due to the users' security. The following ***case studies - from #13 to #16*** - are chosen in this peculiar design area, even if they refer to different targets.

Therefore, a credible design object must be **easily recognizable by the final users**, who need to find in it **familiar characteristics**, otherwise it can be very difficult for them to know how to use it, or how to understand what its function is and then, the consequent effect of surprise could be very negative with a bad impact for their next user-product interactions and for the credibility of the object. For this reason, the object cannot be totally unknow for the end users at first sight. Then, the designer needs to create **a good combination between object familiarity and its ambiguity** - linked to the hidden properties of the material that are not immediate visible by the user but they need an input to change - must be reached to allow the final user to exploit the design product properly. **The designer needs to focus on the users' background knowledge of smart materials**. If the product ambiguity and the visual illusion are too accentuated, the end user could be confused and do not recognise the function / s of the design product. Furthermore, in the first user-product interaction the effect of surprise will be very amplified, compared to the next utilizations, during and after which the user will be more confident in using the product because the smart object ambiguity is not totally new for the user and he will be more satisfied. In fact, he could use **his memories** related to previous product experiences to carry out the activity linked to the design object.

The credibility of an object must be also guaranteed on safety fields, particularly regarding babies for example, as in the ***case study #16***, in which the chromogenic material is used for underlining and communicating a visual alarm for babies' parents, who need to feed the babies without burning them. **The vivid and clear coloured mark between the starting and final material hues** is very appreciated by the parents, who see in the colour-shift contour an attractive chromatic combination and a very surprising effect of the smart object. **The definite mark also emphasizes that a change in the material occured and it reassures the user that the object works**.
Moreover, in other safety fields as the cooking one for instance (***case study #13 and #14***), the users must be sure that the **product is safe and that it guarantees certain performances during the use**. This certainty about the activity achievement is reinforced by an extended period of time during which the user continues to exploit the object and he has good visual feedbacks. This design topic refers particularly to a **long period of use of the object** after

the first user-product interaction - that has the consequent effect of increasing the **user's affection** for the design product. For example, Thermospot (***case study #13***) is a cooking pan that change its colour and pattern in the central part after reaching high temperatures and this fact could be useful for the user while preparing some food, to know the proper temperature at which the food is ready or that is more fit for the specific food he intends to cook. The ***case study #14*** is very similar to the ***#13*** both in functions and context of use.

**After the first interaction with the design object, the user must keep a good memory of the product experience to ease his next user-product interplays with the product**. All the possible user's frustrations connected to the visual feedbacks must be avoided: the time for the colour-shift to appear must be within 10 / 15 seconds after the user's physical contact with the design object; **the activation time of the materials must be chosen properly** and the colour-change cannot be too slow but it is better that it follows rapidly the input stimulation. In conclusion, the previous conditions allow the user to achieve a very good global UX, for instance in objects for beauty and personal care (as in ***case study #15***, in which the different colours of the brush underlines the proper temperature of use for user's hair protection without burning them).

***Fig. 80:*** Case study n.21: Thefal Thermo Spot by M. Grégoire, in the 2000s
Image taken from https://www.tefal.com/about-us/innovation/thermospot

***Fig. 81:*** Case study n.16: Coral Pan by W. Spiga and J. Martins, 2009
Image taken from https://www.behance.net/gallery/339941/Coral-Pan. Author of the image: D. Paronetto, W. Spiga and J. Martins

***Fig. 82:*** Case study n.25: Red line thermochromic brush by Corioliss, 2002
Image taken from www.planethair.it

***Fig. 83:*** Case studt n. 24: Thermochromic spoon for babies' safety, in the 2000s
Image taken from https://materialdistrict.com/material/chromazone/


## CASE NUMBER
#13

## CONCEPT NAME
Tefal Thermo Spot Pan by M. Grégoire

## YEAR
In the 2000s

## CONCEPT DESCRIPTION

The high attraction of the smart pan is represented by its **specially-designed smart indicator,** that makes the cooking a child's play. The end users could cook easily and in total security. Thanks to the good usability performances of the pan, its great quality and its long-lasting characteristics, the user is stimulated to use it more and more due to this object credible features. The spot turns solid red when the pan is perfectly preheated and ready to cook. The thermosensitive property of the pan constitutes part of the pan surprise effect for the user and, combined with the **high quality performances** of use, they **convince the end user to keep using it over time**.

| KEYPOINTS | Smart indicator; high-quality performances; Convincing the user |
|---|---|


## CASE NUMBER
#14

## CONCEPT NAME
Coral Pan by W. Spiga and J. Martins

## YEAR
2009

## CONCEPT DESCRIPTION

The thermosensitive property of the pan has the aim of **alerting the user** from burning accidents that could occur in the kitchen. The colours chosen for underlining and **communicating this message in a more evident way** are characterized by reddish tints and shades that always emphasize the entity of the alarm. The colour-shifts are based on warm and cold sensations on visual level and on the transformation from one to another: the pale blue dots turn into bright orange ones, as the temperature of the pot increases. The dynamic properties of the thermosensitive material represent an extra value and they **enhance the meal preparation and enriches this social ritual**.

| KEYPOINTS | Alerting message; Communicative; Entity of the Alarm |
|---|---|

## CASE NUMBER
#15

## CONCEPT NAME
Red Line Brush by Corioliss

## YEAR
2001

## CONCEPT DESCRIPTION

This case study is related to beauty care and personal safety aimed to people who desire to monitor the temperature of their everyday brush. The colour-shift of the cylindrical brush **indicates the passage from lower temperatures to higher ones** through the red colours of short bristles. The colour chosen could **alarm the user**, who will proceed to comb his own hair with more caution. The surprise effect is not so pronounced here but the **credibility and reliability of the product are guaranteed** and based mainly on the **quality of performance** of the thermosensitive material. **More the quality of the material is assured, more the user will keep to use the design product over time.**

KEYPOINTS: Reliability; Temperature indicator; Performance quality; To ensure the end user

## CASE NUMBER
#16

## CONCEPT NAME
Chromazone pigments by TMC Hallcrest

## YEAR
2004

## CONCEPT DESCRIPTION

The smart spoons are credible tools that parents used to feed their children. **The safety characteristic lies in the immediate and vivid colour-shift after the spoon reaches high temperature**, that could be dangerous while nourishing the baby. **The marked colour-change** is very appreciated by the end users because it creates a sense of surprise but it also alarms them that something in the material has changed. The colour-shift could be characterized by a **fading effect**: the lively purple colour becomes light pink). This fact **emphasizes the user's astonishment because it is like the spoon is losing its own colour, becoming clearer**.

KEYPOINTS: Safety characteristics; Marked colour-change; Fading effect

| | |
|---|---|
| HONEYCOMB DIAGRAM PRINCIPLE | CREDIBILITY |
| DEFINITION | *An object is credible if the final users can rely on it during their first product experience and also over time, and if they are encouraged to believe in what the product tells them due to its simply understandable functionality.* |
| DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS) | 6. The credibility is required in special contexts, as the safety field, and the designer must provide a proper guarantee of usability to the user, through the chromogenic properties (e.g. **the definite colour-shift mark emphasizes that a change in the material occured and it reassures the user that the smart object works.**)<br><br>7. The designer needs to create **a good combination between object familiarity and its ambiguity** linked to the hidden properties of the material that are not immediate visible by the user but they need an input to change. From this condition **a surprising first UX could occur and consequently it will ease his next user-product interplays with the product**. |
| CASE STUDIES | #13, #14, #15, #16 |
| KEYWORD PHRASES | Safety fields; Definite color marks;<br>To reassure the user;<br>Familiarity / ambiguity balance;<br>UX memory |

### *ACCESSIBLE*

A smart product is accessible when it meets as much as costumers as possible without the necessity of special adaptation but meeting people's needs.

**The surprise effect could be used as a valid tool for enhancing the product experience for every kind of people and for creating a valuable social context of usability**. Regarding this subject, the valence of colours and especially of colour-shifts have a great importance because they embellish the collective or private spaces radically transforming the user's perception of the environment. **The smart materials allow the user to interact with the environment in a less complex way. The designer should adapt the visual appearance of the smart object to environement conditions,** making the thermochromic materials very attractive in fields such as architecture (***case study #18***) or interior design (***case study #17***).

The accessibility of a product has a particular connotation: it refers to the understandibility of the smart object message and its modality of being easily appreciated by every kind of people. The thermochromic materials could be universally used for many different purposes that could aim every person, adding new and valuable meaning to the final user experience. **The designer's intent should be the creation of a valuable environment in a design panorama related to human social living. These design products need to communicate pleasantness due to the special properties of the chromogenic material they are made of , their sensorial perceptibility, the use of the object with the least effort possible.**
For instance, in ***case study #18*** the urban environment could be perceived enhanced by people who live in the city and it creates a very surprising and innovative social experience for almost everyone.

To make the surprise effect accessible by as many people as possible, it must be precisely projected. The designer should choose the precise information conveyed by the product and they need to be coherent with the context of use. In order that the surprise effect of the smart object could be accessible, the designer should take care of **the user's perception.** For example, in products characterized by a high level of complexity of use and know-how, the surprise emotion will be not so appreciated by the end user. If the design product is a very functional tool whose main aim is to reach a specific objective in a short time and very accurately (e.g. screwdrivers, drills), the surprising smart characteristics must be avoided because they could make the product accessibility more difficult and they could prevent the satisfaction of the user's need *(e.g. fix a screw)*. On the contrary, **if the design products are low-tech and they are characterized by easy and immediate modality of use and a cleare objective, the surprise effect is more accessible because it does not require a cognitive effort for the end user related to its usability (e.g. wallpaper, building).**

***Fig. 84:*** Case study n. 17: Thermochromic Wallpaper by S. Yuan, 2013
Image taken from http://www.wallpaperink.co.uk/blog/5-crazy-wallpaper-ideas-that-are-actually-real/. Wallpaper Ink, Interior design blog
***Fig. 85:*** Case study n. 18: Thermo Tiles by W. Lian, 2017
Image taken from https://www.designboom.com/project/thermo-tiles2/


**CASE NUMBER**
#17

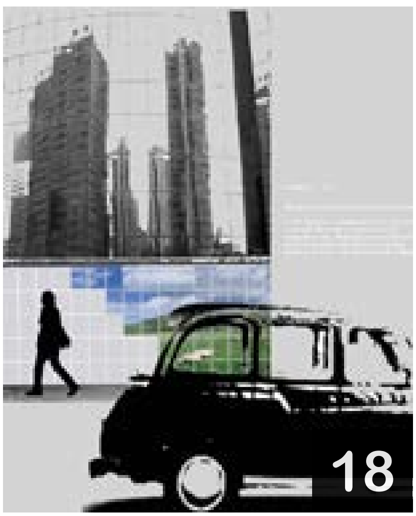
**CONCEPT NAME**
Thermochromic Wallpaper by Shi Yuan

**YEAR**
2009

**CONCEPT DESCRIPTION**

The smart wallpaper is an accessible design product because its **visual appearance is adapted to environment conditions** and different people could appreciate it. Its accessibile **dynamic properties** do not necessitate special user's cognitive efforts to be understood and they **simplify the user's interaction with the environment**. In fact, after the first product experience, which a starting surprise emotion could result from, the user could comprehend very fast the wallpaper **functionality**, based on the association between an increase of the room temperature, and the contemporaneous appearance of pink flowers on the wall paper.

| KEYPOINTS | Visual appearance; Dynamic properties; Simplification of user' interaction with the environment; Functionality |
|---|---|




**CASE NUMBER**
#18

**CONCEPT NAME**
ThermoTiles by Wei Lian

**YEAR**
2004

**CONCEPT DESCRIPTION**

The designer's starting point to develop this design concept lies in **adapting the thermochromic material to building tiles**, in order to change and to **enhance the human environment** which people live in. This case study represents a good example of smart idea that could improve the aesthetics of several collective places through an **immediate** emotion of surprise that is created after user's first visual experience with the special properties of the tiles.

| KEYPOINTS | Enhancing the human environement; Immediate surprise |
|---|---|

HONEYCOMB DIAGRAM PRINCIPLE

ACCESSIBILITY

DEFINITION

*A smart product is accessible when it meets as much as costumers as possible without the necessity of special adaptation but meeting people's needs.*

DESIGN GUIDELINES WHICH THE DESIGNER SHOULD FOCUS ON (FOR DESIGNING SURPRISE THROUGH THERMOCHROMIC MATERIALS)

8.
Focus on the creation of a surprising environment for human social living. Smart products need to communicate pleasantness due to their special properties, the sensorial perceptibility, the use of the object with the **least effort possible:**

- **Focus on low-tech** smart product (characterized by easy and immediate modality of use and a cleare objective) so that the surprise effect could be accessible because it does not require special user's cognitive effort;

- The smart materials allow the user **to interact with the environment in a less complex way making the UX more accessible.** The designer should adapt the visual appearance of the smart object to environment conditions.

CASE STUDIES

#17 #18

KEYWORDS

Valuable and surprising environment
Least effort possible of the user;
Low-tech smart objects;
Less complex user-environonment interaction

### DESIGN GUIDELINES SUM UP

A summary scheme is described here to have a global idea of the design guidelines previously proposed for projecting surprise through thermochromic and hydrochromic materials. The design guidelines are eight and they are numerically identified.
The designer could follow the order given here - that is suggested but not mandatory - to verify that his project could respond to the different attributes needed for a valuable and surprising UX. Every design product is characterized by a specific balance between the six attributes of the Honeycomb diagram - according to which the design guidelines are structured - compared to other design products.

**USEABLE**

**1. The designer should focus on the uniqueness and personal user-product interaction that must be as much unrepeatable and intimate as possible:**

- Focus on the smart object interface;
- The number and type of parts that will be touch by the end user;
- Letting the user merge into the smart product;
- The interactive product could behave as a human being (attribute human characteristics to the product);
- The alive smart material properties could reflect the character of the design product and its function.

**2. Focus on the contrallibility of the smart object**

- hand pressure, activation and relaxation time and temperature;
- The long lasting mark is more appreciated in terms of surprise.

**USEFUL**

**3. Focus on the context of use:**

**a. PUBLIC**:

- To break up the monotony of everyday life (while waiting e.g.) through the smart properties of the thermochromic material;
- To avoid stressful and chaotic situations in which the user is under pressure (e.g. commercial contexts) and he could not understand the smart properties of the material;

**b. DOMESTIC**:

- focus on one-time emotion and socialization originated from the smart object (it increases its value over time not losing user's interest)
- The designer should focus on aesthetic / functional aspects of smart objects to trigger user's emotional system (e.g. the smart object personalization leads to a more personal and affective product experience over time)

**DESIRABLE**

**4. Focus on the strategy for activating curiosity and interest in the final user through:**

**a.** The combination of vivid and intense colour-shifts and odd product shapes;

**b.** The use of the smart material to create fun for the end users to stimulate his interest and to create a globally positive UX;

**c.** Disregarding user's certainties related to everyday and simple object to emphasize his final emotion of surprise using thermosensitive materials (**Opposite Techniques**: e.g. a stain becomes a beautiful pattern)

**FINDABLE**

**5. Communicating the colour-shift and the hidden nature of the smart material in an immediate and easy way ( avoiding negative visual feedbacks of smart material properties):**

**a.** For designing a surprising **user-product experience** using chromogenic materials, the colour-shifts could increase the functionality of the final product if they are associated to correct and uncorrect use of the object;

**b.** The designer should focus on the possibility to adapt the external environment conditions as a tool for making the smart material more informative (e.g. rain)

**CREDIBLE**

**6.** The credibility is required in special contexts, as the safety field, and **the designer must provide a proper guarantee of usability to the user through the chromogenic properties** (*e.g. the definite colour-shift mark emphasizes that a change in the material occured and it reassures the user that the smart object works*);

**7. The designer needs to create a good combination between object familiarity and its ambiguity** linked to the hidden properties of the material that are not immediate visible by the user but they need an input to change. From this condition a surprising first UX could occur and consequently it will ease his next user-product interplays with the product.

**ACCESSIBLE**

**8.** Focus on the creation of a surprising environment for human social living through smart products that need to communicate pleasantness with the **least effort possible:**

- **Focus on low-tech** smart product so that the surprise effect could be accessible because it does not require special user's cognitive effort;
- The smart materials allow the user **to interact with the environment in a less complex way making the UX more accessible.** The designer should adapt the visual appearance of the smart object to environment conditions.

7

# CONCLUSIONS & FUTURE PROSPECTS

# 7. Conclusions and design perspective

## 7.1 Colour-shift vs faster learning and understanding of design product function

Colours influence and catch users' attention and they are used in marketing strategy to drive potential users' purchases. It was demonstrated that for instance a red button for a call to action service can increase the conversion rate of about 21% compared to a green button. The reason of this fact is due to the more engaging visual impact of red colour on a bigger number of customers. Moreover, the psychological influence that colours have on users' shopping are strictly linked to a better understanding of products functions and to the comprehension of how they really work while in service. In fact, **colours increase and improve the comprehension of advertising messages at about 73%; they facilitate and help the learning of advertising contents at about 55-68% more than black and white messages and finally they simplify an advesrtising text message at 40%.** [104]
With chromogenic materials the same effects could be created because they drive emotions in a more powerful way, and in addiction they trigger the surprise effect. Then, the information contents of products made of colour-changing materials are directly embedded in the materials and they could catch potential users' attention with more semplicity and with less difficulty because their colour-shift is a special phenomen and it is not so well known among people.
Furthermore, if the colour-changing materials are very well designed, they can drive the products information for letting potential customers better understand the functions of the design product in order to be purchase and be purchase faster. The information contents could be enhanced and underlined by chromogenic materials and they are strictly linked to user-product interactions due to the dynamic aspect of the colour-change and the external inputs it needs to be activated.

104 Tecchia M.G., (2015), Comunicare sul Web, https:/www.google.com/amp/www.comunicaresulweb.com/web-marketing/quanto-i-colori-influenzano-i-nostri-acquisti/amp/

## 7.2 Do colour-changing materials affect and improve personal out-comes such as human understanding about learning achievement?

The persective question which the thesis could end with, is connected to the use of the surprise effect to help people to improve their own understanding during learning activities. It represents a wide and almost new scenario in which the use of chromogenic materials could take hold. The surprise emotion related to these special materials - principally the thermochromic ones - could enhance the teaching and learning modalities due to their particular physical characteristics linked to the human visual and tactile experience.

After an unexpected external stimulus, the human analysis and its evaluations that could follow, allow to get a more detailed knowledge of the extraneous event. This fact could be useful for guarantee a more solid base for the overall human knowledge system. In fact, an unexpected UX could modify the previous knowledge background through the addition of newer psychological schemes after the user-product interaction.

**The learning activities, as Berline (1971) assumed[105], consists in the rainforcement or impairment of the human stimulus - reaction associations after facing some special situations in the external environment.** In fact, if the external stimulus is lived for the first time by human beings, it could be linked to a particular human reaction but, if the two variables are already associated, the starting stimulus could be experienced in a more strong and powerful way, fortifying the memory of the previous user-product experience.

The surprise effect could be understood as the beginning for a more wide vision of the world and its phenomena, through an increase of human interest and allowing the knowledge of newer things around, starting from what human beings already know. Then, it allows the individuals to improve the extension of their general understandig and comprehension of the wordly things around them.

Moreover, the emotion of surprise could maximize human memories related to previous special experiences because the details of the event remain more impressed in human memory due to the unexpected behaviour of the event. For this reason, compared to a non-surprising experience, the surprising one

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could be considered a valuable tool during learning activities such as the ones that take place in schools or universities but especially during the first stages of human life ( e.g. at the nursery).
In conclusion, thanks to the special features of the emotion of surprise, that is characterized by a very careful assignment and distribution of human mental and psychological resources, the focus on the unexpected event is maximum. This fact could open a very wide range of opportunities for next designers for projecting surprise through thermochromics.

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