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Paving the way to post-digital smart materials. Experiments on human perceptions of a bio-inspired cellulose-based responsive interface.

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Abstract | The paper aims to frame the emerging scenario of hybrid interactive systems, and pave the way for post-digital interactive materials, proposing organic material interactive interfaces as a potential alternative to digital and electronic-based ones. Supported by the theoretical background and related works, a case study developed by one of the authors is presented: a cellulose-based interactive interface where the material itself work as a sensor and an actuator. This new generation of smart materials enables and implies novel experiential patterns to observe and discuss. An exploratory workshop on this novel typology of material interface carried out by one of the authors is then described addressing the critical issues of users' perception and appreciation. The methodology of the activity is based on quantitative and qualitative data collection through a questionnaire made of scale questions and open-ended questions, plus direct observation and discussions with the participants. The activity integrates the lens of Materials Experience, in order to overcome the missing understanding of the experiences enabled and implied by this interface. Prominent findings unfold the relationship between temporal and static expressions. Finally, biomimicry arises as an approach to transfer the feeling of nature and to create more intuitive interaction.

KEYWORDS | MATERIALS EXPERIENCE, BIOMIMICRY, CELLULOSE-BASED INTERFACE, HYBRID MATERIAL SYSTEMS, RESPONSIVE MATERIALS

1. Introduction

In the research and practice around material design, different post-digital scenarios are currently emerging. Computers, as we know them today, will disappear into things that are, first and foremost, something else (Negroponte, 1998).

The paper aims to frame the emerging scenario of hybrid interactive systems and pave the way for post-digital interactive materials, proposing organic material interactive interfaces as a potential alternative to digital and electronic-based ones. Supported by the theoretical background and related works, a case study developed by one of the authors is presented: Transformative Paper (Holzbach, 2015a), a cellulose-based interactive interface where the material itself works as a sensor and an actuator.

Comparing to traditional electronic-based smart materials, this newer generation of hybrid interactive materials enables and implies novel experiences and opportunities of combining dynamism and authenticity. The experiential patterns mediated by the formal and behavioral qualities of such materials need to be explored and discussed. Therefore, an exploratory workshop on this novel typology of material interface carried out by one of the authors and involving a selected group of participants is then described addressing the critical issues of users' perception and appreciation. From this activity, promising preliminary results on people perception emerge and set the base for further research actions.

2. Theoretical background and State of the Art

2.1. Hybrid Interactive Systems

Today, besides objects equipped with artificial "intelligence," materials themselves may be informed and rewritten by micro-scaling digital or procedural activities. Micro-scaling can lead to the hidden information of traditional materials and everyday objects surrounding us. This results in an aesthetic and functional augmentation of existing materials that infuse materials of "living" or "intelligent" qualities. At this stage, new properties are usually constructively linked to the material on a macroscale level and in a traditional way – for example, through layering.

This brings to the emergence of materials with responsive behaviors that can detect, process, and manifest data. "Smart materials" is a relatively new expression used to identify materials that have changeable properties, in opposition to traditional materials that are latent (Ritter, 2006). They can change some features like shape or color in response to physical or chemical influence from the environment or the users' body.

It is often possible to combine several materials with smart properties together to create *Smart Material Composites* (Barati et al., 2019), and to combine actuating, sensing and controlling electronics into *Smart Composite Material Systems* (Kelly, 2017) in order to increase the smart qualities of the final product. The combination of organic and inorganic components, including micro components such as electronics leads to the definition of *Hybrid Materials* (Saveleva et al., 2019; Ritter, 2006). As a result, *Hybrid Material Systems* (Parisi & Ferraro, 2021, p. 127) are defined as “material-based systems encompassing different components such as inactive materials, smart material components, sensors, actuators, computational layers”.

Due to the increasing miniaturization of technologies, the seamless integration of sensors and actuators into materials have been theorized and envisioned in the notion of *Augmented Materials* (Razzaque et al., 2013*), Expanded Matter* (Brownell, 2014), *Computational Composites* (Vallgårda & Sokoler, 2010), *Material programming* (Vallgårda et al., 2017), and *Interactive, Connected, and Smart (ICS) materials* (Ferrara et al., 2018; Rognoli & Parisi, 2021).

While at the beginning the first wave of digitality affected drawing and visualization tools for design, then digital production tools and the process chains derived from them followed. The resulting connection of the digital with the physical – or the material – results in directly derivable hybrid structures with their own hybrid property profiles. This results in a formal and functional augmentation of existing materials, that infuse materials of "living" or "intelligent" qualities. Hybrid materials are multi-layered and heterogeneously informed. As a result, materials are becoming increasingly informative and intuitive.

Some hybrid Interactive systems are designed by using designed Materials. This leads to the question of whether the discussion about constructions that are suitable for the material or design which is suitable for the material is outdated or not. Today, materials are developed to perform a task. The question of materiality arises as a central decision and development at the beginning of a design task and not as a selection from existing materials at the end of the project (Parisi et al., 2020). Material-oriented design is increasingly turning into “design with designed materials” (Holzbach, 2015a).

2.2. Material Authenticity

Many of today's material solutions integrate new technologies and components, and their scale and complexity no longer allow conclusions to be drawn about their performance or function. This is also the ambivalence of the material solutions presented here in the paper. In the articulation of these new and hybrid material solutions lies the important cultural mission of material design (Holzbach, 2015a)**.** In most cases, designers look for a suitable material for their design or design the product with a specific material in mind. This "material authenticity" – i.e. what a material intrinsically is and naturally does – seems to be overcome.

Today, the world of materials, substances, and semi-finished products meets digital design and production methods, changing the conventional idea of material “authenticity”. This fundamentally changes the way design concepts are conceived and leads to entirely new ways of thinking. Today, materials are rather developed for their task. "Materials with sensitive, smart, or gradually varying properties lead to new and complex design concepts. This opens up new possibilities at the level of concept, form, structure, and surface. The path from static to dynamic, process-oriented properties is thus smoothed." (Holzbach, 2014a, p. 69). As Sabine Kraft writes:

> "The relationship between form and material has become as diverse as it is ambiguous. A recourse to clear rules and specifications as to what can be conceived and constructed in which material and how, and which aesthetic message would be transported by this, is hardly possible anymore - if it ever existed." (Kraft, 2004, p.24)

"Informed" or "augmented" materials with sensitive or smart properties, thus lead to an increasing blending of different contexts. Mixed forms emerge that no longer allow a clear separation. As a being of our time, the increasing intertwining of the most diverse areas of life and knowledge can be seen. New material and design concepts are also acting in this context, resulting from the overlapping of digital and analog, nature and artifact. It is the interdisciplinary process that see and define material, form and construction as a holistic unit. Where is the border between real and fake, natural, and artificial?

What meaning can the term material authenticity still have in our digitized world? The digital, in particular, is predestined to connect different sensory levels. In the digitalized world surrounding us, and especially in contemporary art and cultural positions, such border crossers in the intersection of Art and Science or Design and Technology are of increasing importance. To what extent do nature and the artificially created interact to create a new form with its own hybrid characteristics? Where does something begin, and where does something end?

A permanent comparison of information and materialization takes place. In addition to the digital programming of materials, specific material parameters can continue to be embedded in the digital models. "It is precisely the dialogue of the "real" material with the "virtual" and "dematerialized" digital world that leads to new formal and functional impulses and contexts" (Holzbach, 2014b). The virtual and the real are interwoven and thus lead to new hybrid property and design profiles. Analog and digital material concepts and their hybrids become the carriers of information. Materials become informative or even intuitive, enter into a dialogue with their environment and thus have new functions of meaning. The material acts at the interface of the digitalized and real world. The traditional thought pattern of "material-authentic design" is broken through the link between digitization and materialization. Here a substitution of important digital components in favor of natural materials is taking place. The material itself takes over essential tasks and increasingly seems to have intrinsic qualities.

2.3. Post-digital Interactive Materials

In a future perspective, the possibility to substitute traditional electronic components, even with bio-based or bio-inspired ones, is not remote. In the first German edition of Domus, Mateo Kries (2013), director of the Vitra Design Museum, writes: “Museums today must treat design as what it is – as a cross-sectional discipline between art, science, and technology”.

Nature, with its structures and constructive laws, often serves as a valuable source of inspiration for material design as well as new technologies, through biomimicry (Salvia et al., 2009) and the cooperation of digital manufacturing (Langella, 2007). Recent definitions of *Bio-Smart materials* (Lucibello et al., 2018; Ferrara et al., 2019) and *Bio-Synergistic materials* (Parisi & Shetty, 2020) elaborate the mechanical and biological response to stimuli of natural-based materials as a medium of smart behaviors.

One challenge for the development of hybrid material systems is the one of sustainability, in particular the use of non-toxic, renewable, and biodegradable materials. The integration with biodegradable materials and fibers may allow the separation of components. This is the case of interactive wearables and objects using mycelium as a support and structure for electronics (Lazaro Vasquez & Vega, 2019), or the use of bioplastics for robotics (Kretzer & Mostafavi, 2021) or transient electronics (Tao et al., 2012). An example of design experimentation is a conductive bio-skin made by growing bacterial cellulose with conductive compounds by designer Giulia Tomasello (Fig. 1).

Figure 1. Conductive Bio Skin experiments by Giulia Tomasello.

However, the use of materials with changing properties is not an invention of modern times, and those responsive behaviors can be found in nature (Ritter, 2006). Examples of organic materials and micro-organisms enabling aesthetic and functional dynamic responses in fashion and product design can be found in the literature. In this respect, biological organisms can also be used as biosensors and bio-actuators to replace synthetic ones.

This is the examples of BioLogic (Yao et al., 2015), a textile which uses the mechanical behavior of Natto bacteria masses deposited on portions of textile to respond to moisture (Fig. 2). The bacteria’s body enlarges with humidity allowing the textile to change shape. Other examples of biosensors are Organic Primitives (Kan et al., 2017), pH-reactive organic materials used for sensing, actuation, and interaction, (Fig. 3) or the use of bioluminescent organisms for performing light-emitting behaviors.

Figure 2. BioLogic by MIT Media Lab (Lining Yao), 2015 (photo by Rob Chron).

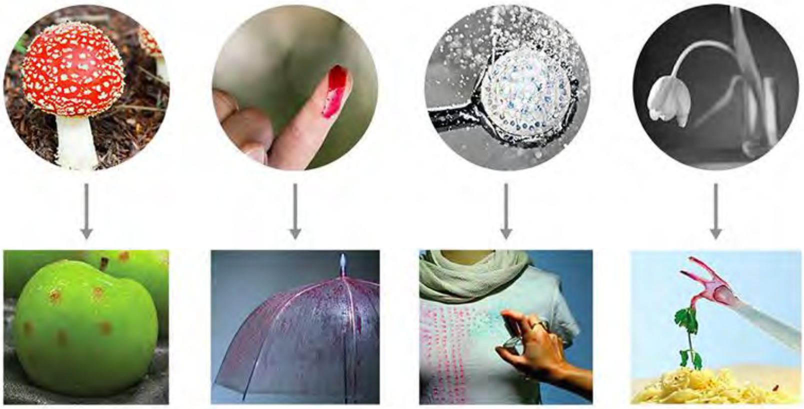

Figure 3. Organic Primitives by MIT Mediated Matter Lab (Viirj Kan).

Researchers and designers are exploring the smart behaviors of traditional materials supported by digital manufacturing and parametric design, such as organic pulp-based surfaces and fibers reacting to moisture. Programmable knitting (Scott, 2018) tested the shape-shifting moisture-responding anisotropic behavior of pulp-based fibers woven into textiles to determine the geometry related to each deformation and integrate it in the design process by using parametric design (Fig. 4).

Figure 4. Programmable Knitting, by Jane Scott, 2018. On the left: growing medium profile. On the right: Shear, after actuation (photo by Cristina Schek).

This newer generation of hybrid and post-digital materials also shows the reactive properties of the natural world. However, the post-digital and bio-mimetic materials show authentic properties connected intrinsically to the material. The combination or description of new properties via micro-scale digital or procedural components is perceived as an embedded "intrinsic" property and as inherent to the respective material. The properties of the living are conveyed even more strongly in these materials, since the material apparently reacts automatically to its environment. The hidden individual components lead to the suggestion of existing formal and functional properties in the material itself. These are per se not present in the actual material or artifact, but rather result from the hidden current and operating properties.

The traditional nomenclature of design and its semantics is at this point undermined. The encoded and rewritten material can no longer be decoded with a classical sign function or described with questions about "material authenticity". The product language, which acts out of its symbolic or symbolic nature, can therefore no longer be used as an unrestrictedly effective means. Instead, the object is "intuitively" or even "not" accessible. Our existing, object-like environment is able to communicate, but no longer communicates this to us - in the sense of a classic sign function - as it used to.

3. Case Study: Transformative Paper

A case study of post-digital interactive material developed was developed by one of the authors as a result of a student's project and is presented in this section. Similar to Programmable Knitted by Jane Scott (2018), the authors' case study is a cellulose-based interactive interface in which the material itself works as a sensor and an actuator. It is a shape-changing multi-layered surface made of paper combined with a plastic layer and cut in small bio-inspired segments reacting to short-term environmental conditions, as a combination of the properties of the material and the designed shape. Depending on the air humidity, the paper structure morphing without electronically based sensors into various states (Holzbach, 2015b).

The project Transformative Paper (Fig. 5) was developed in a collaboration between the Institute for Materialdesign at the Offenbach University of Art and Design and the company BMW. A whole series of different concepts of responding surfaces was created under the guiding theme "Intuitive Brain." These surfaces were developed by students by using different interpretations and perspectives around the theme, which convey the “intuitive” meaning in different ways.

Figure 5. Transformative Paper by Florian Hundt, a result of the cooperation "Intuitive brain" between Prof. Dr.-Ing. Markus Holzbach, Institute for Materialdesign IMD, HfG Offenbach and BMW AG, 2015. The interactive surface uses the anisotropic condition of papers, in combination with a plastic film, to perform a dynamic behavior when triggered by moisture.

In this particular case, the responding capability of the project is based on the notion of anisotropy: a condition in which specific material properties can vary depending on the direction. This also applies to wood and especially wood veneer with its fiber-based structure. In the first conceptual, preliminary stage, the interaction of the veneer wood and its anisotropy with the macrostructure consisting of different fractals has already been established. Depending on the moisture distribution to the used wood species, and according to the orientation of the veneer wood, different forms can be realized. For instance, a one-sided moisture supply leads to corresponding swelling processes in the wood. This leads to tensions and deformations in the wood.

This behavior is reversible, and the process is reversed with increasing drying. The material and thus also the structure resume their original form. Controlled by the alignment of the veneer modules, "intelligent" structures become conceivable, which react to both the absolute humidity and the distribution of moisture in the room and which can fulfill specific practical and aesthetic functions through their three-dimensional deformation. The reactive surface serves as both a sensor and an actuator (Fig. 6).

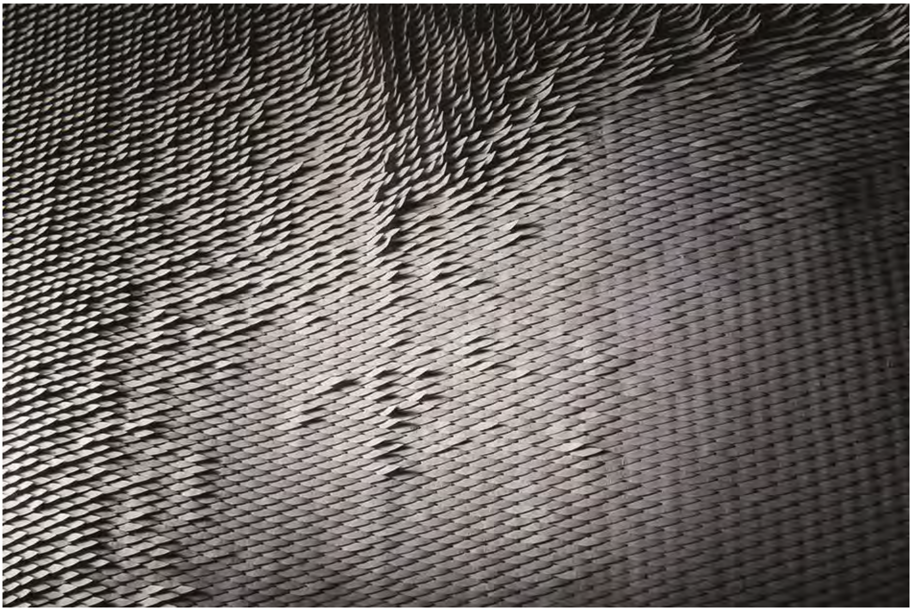

Figure 6. Transformative Paper by Florian Hundt, a result of the cooperation "Intuitive brain" between Prof. Dr.-Ing. Markus Holzbach, Institute for Materialdesign IMD, HfG Offenbach and BMW AG, 2015. A detail of the interactive surface.

Basing on this logic, the behavior of anisotropy should be exploited in further development. Up to now, wood has been the most commonly used raw material in paper processing. Since paper is made directly from the wood, it has the same swelling behavior and also the anisotropic properties of wood. Conventionally, these effects, which result from the anisotropy of the starting material, are undesirable, especially with machine-made paper and in a wide range of areas of application. On the contrary, isotropic properties are desired, i.e., materials whose property profiles are the same in different directions and thus homogeneous. However, In the development of the project, a series of tests were performed in order to investigate and verify the anisotropic behavior of wood. For example, according to the type of wood, growth conditions, and other variables, different properties are obtained in different growth directions. Strengths, swelling behavior, and deformation behavior can be predicted quite precisely. In particular, in the scope of the work presented here, the effects resulting from anisotropy are of particular advantage.

After all, in a post-digital scenario, the adaptive and interactive qualities of materials are expected to be developed from an authentic and inherit – "intuitive" – material intelligence and without the addition of a digital component. Thus, specific deformation properties can be introduced into desired areas of reactive surfaces in a very targeted manner. The individual fractals are integrated into the overall surface and positioned individually, quasi tailor-made.

The main goal of the presented work "Transformative Paper" was formulated as the independent response of an interactive automotive skin to the influence of the weather and especially to the interaction with rain. The developed reactive skin reacts automatically and is intuitively able to adapt to the weather. If one makes use of the anisotropic properties of the paper and combines the paper with other materials, new areas of application and contexts can be opened up. In this case study, the paper layer was constructively combined with another plastic film in a multilayer construction. The resulting multilayer construction reacts continuously to environmental influences. Depending on the humidity, the paper structure is transformed into different states. This results in a gesture that can appear so subtle when humidity is low that the transformation is not evident at first glance. The transformation takes place more evident when the surface is exposed to moderate moisture and heavy rain. If the structure is dried, the individual segments will stand up. When wet, the structure closes entirely automatically and without digital control or regulation (Holzbach, 2015a).

4. Exploratory workshop on users' perception

A challenge for design research is identifying meaningful ways to design with and for materials like this. They imply complex and novel experiences that designers need to comprehend and implement to foster people's appreciation and acceptance (Parisi & Shetty, 2020).

An exploratory workshop on this novel typology of material interface involving a limited number of selected participants was carried out by one of the authors and is here described addressing the critical issues of users' perception and appreciation, and to overcome the missing understanding of the experiences enabled and implied by this interface. In particular, the object of the study is Transformative Paper, by the collaboration between the Institute for Materialdesign at the Offenbach University of Art and Design and the company BMW AG, the one broadly presented in the previous section of the paper. The study was organized in the format of a workshop with users, aiming at unfolding qualitative patterns (Petrelli et al., 2016), using the lens of Materials Experience (Karana et al., 2015; Giaccardi & Karana, 2015). The setup, methodology, and results of the study are thoroughly described in this section.

4.1. Methodology

The activity was organized in the format of a small workshop of 1 hour and 30 minutes. The activity was performed at the School of Design of the Politecnico di Milano. The study involved 20 participants, including design students (13), practitioners, (4) and scholars (3), from 4 different countries, i.e., Italy (13), Portugal (5), Brasil (1), Perù (1).

The methodology of the activity is based on quantitative and qualitative data collection through a questionnaire made of scale questions and open-ended questions, plus direct observation by one of the authors and discussions with the participants. The activity was divided in four subsequent phases:

- exploration and analysis of the static form and expression of the material;
- exploration and analysis of the dynamic form and expression of the material;
- comparison with other dynamic materials, i.e., thermochromic painting, electroluminescent ink, shape-memory alloy spring, and oxidizing copper;
- participant’s background, previous knowledge and final remark.

The lens used to observe and analyze the item is the one of Materials Experience. Each of the moment was introduced by small presentations by the author, with the support of projected slides, including the introduction of grounding theoretical notions with examples and showcasing of the samples. A coded envelope and four papers containing questions and scales related to each of the four phases, namely part A, part B, part C, and part D, were distributed during the execution of the activity to each participant as a compass to the activity and to collect data. After each moment, before explaining the following part and distributing the related paper, the author encourages a moment of discussion with the participant in order to unfold key issues in the scope of the research. The language use for the questionnaire, the execution of the activity, and the discussion was English. Participants were asked to fill the questionnaire and express their opinion in the discussion in English or in their mother language if that made them more comfortable. This was appreciated when allowed to provide more accurate and complex description of feelings and recalls in the participant’s memory.

The questionnaire was set as follow:

Part A: the sample is shown in its static expression. A sensorial evaluation scale (Karana, 2009) was provided to support the evaluation of the samples.

- How would you describe the material?
- Which are the main sensorial qualities?

- Which emotions, feelings and memories does the material elicit in you? Why?
- Which adjectives/meanings would you use to describe the material? Why?
- How would you approach and interact with the material?
- How would you think it would change in time?

Part B: the sample is shown in its dynamic expression.

- How would you describe the behaviour of the material? What are the inputs? What are the outputs? What are the qualities of the behaviour?
- Which emotions, feeling and memories does the behaviour elicit in you? Why?
- Which adjective/meanings would you use to describe the behaviour? Why?
- Look at the previous paper (paper A): is the experience elicited by the material changed? What in particular? Think about the sensorial qualities, emotions, meanings, way of interacting or approaching the materials. Would you change the nickname of the material?

Part C: other materials showcasing dynamic behaviors are shown and compared.

- Describe the different experiences resulting from the materials and related behaviours. Use the questions in the previous page (paper B) as a guide for the description.
- Put the different experiences in order of preferences and explain why?

Part D: questions for demographic data (age, nationality, job), previous knowledge on the topic (Transformative Paper, Materials Experience, Smart and Interactive Materials), and optional comments are contained.

Paper questionnaires and audio recording of the activity were digitalized and transcribed by the author in tables. Comments and answers in mother language were translated by the author. Once transcribed, data were analyzed by the author in order to extract patterns, contradictions, and key considerations.

Figure 7. Two phases of the exploratory workshop, carried out by Stefano Parisi, Polimi, 2019.

4.2 Results and discussion

Among the results, prominent findings unfold the relationship between temporal and static expressions. For instance, slow bio-inspired responses and the principle of accordance between shape, material, and behavior evoke positive connections.

In particular, the behavior and dynamic expression influence the experience (Rognoli, 2015), modifying all the layers of experience. Some people had a positive reception to the materials, mainly related to the feeling of surprise and wonder, while to other the behavior itself was considered as aggressive. Slow behaviors are considered more evocative and emotional. Diffusely, the behavior was considered as natural and assimilated to vegetal elements. Thanks to the behavior the materials was considered as "alive." This was considered positively. Some participants underline the fact that the material, in the static dimension, suggested how the material would move, by reminding a field of grass. This accordance appears to be key.

Biomimicry arises as an approach to transfer the feeling of nature and to create more intuitive interaction. Most of the participants are encouraged to interact with the material when static, while when reacting at first preferred to observe instead of touching.

In this case, the input (water) not only trigger the behavior (shape-changing), but changes the qualities of the material itself, making the materials wet and softer, which is perceived by participants as more fragile or comfortable. The natural transformation of the substrate with time (e.g. ageing) may interact with the reversible behavior.

Limitation of the activity is related to the diversity of samples provided, in terms of shape, applications, and details. In fact, while the main object of the study was considered by the participant as a designed material system with a high artistic value, the other samples used for the comparison – namely, thermochromic painting, electroluminescent ink, shape-memory alloy spring, and oxidizing copper – didn't have the same complexity and were considered as material samples. Plus, among these material samples, some of them were designed for a specific application. In general, the items didn't have common characteristics that would make the comparison more objective, i.e. size, thickness, colors, surface qualities such as texture, performance qualities such as flexibility. While Transformative Paper had a proper showcasing divided in two moments leading the participants to explore thoroughly its static and dynamic dimensions, the other samples used for the comparison didn't have the same space for presentation and showcase. Another limit is represented by the small sample of participants involved and by their robust relation with the area of design and materials. Following studies may involve unskilled participant, unfamiliar to the topic.

5. Conclusions

Concluding, the paper presents the emerging scenario of hybrid interactive systems and paved the way for post-digital interactive materials. In particular the authors used a speculative approach to propose organic material interactive interfaces as a potential alternative to digital and electronic-based ones. Supported by the theoretical background and related works, the authors demonstrated the potential of this novel area of advanced materials, in particular the ones related to intuitiveness and authenticity of the interaction and communication between the users and material interfaces. Secondly, the challenge of sustainability is promoted by the use of organic and natural interactive components, instead of digital, chemical, and artificial ones. A case study developed by one of the authors is presented: a cellulose-based interactive interface where the material itself works as a sensor and an actuator. An exploratory workshop based on the notion of Materials Experience on this novel typology of material interface carried out by the authors validated the hypothesis of the beneficial impact of such materials in enhancing meaningful and positive experiences for the users. Not only, it triggers complex interplays between the behavior, the shape, and the material qualities opening up to original ways of designing and experiencing the artifact.

Although the exploratory workshop is conducted with a narrow, insular, and small number of participant and to date has not been repeated yet, it presents some interesting and promising insights to use as a base knowledge for further research actions. The methodology of the exploratory workshop can be considered as a pilot or prototype for a more in-depth user study.

The authors underline that the case study is analogic and does not use embedded technology and smart components to react. However, it is key to the study as an example of dynamic materials, in order to retrieve information to use not only for the development of post-digital interactive materials, but to extend to smart materials with embedded electronics, in order to reiterate positive experiences. Indeed, data obtained from the studies are intended to be applied to the design of hybrid material systems as part of a broader methodology.

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