Lisboa, FA ULISBOA, February 2023

Scientific Dissertation developed for
obtaining the Master Degree in Interaction Design

Research through Design approach for AI-enhanced Interactive Print

Master Applicant: João Rafael Cruz Abrunhosa
Supervisor: Prof. Marco António Neves da Silva, PhD.

President of the Jury: Teresa Michele Maia dos Santos, PhD.
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To the dreams that I wrote down, and have since come to life,
Even though my heart was in the future, I always knew it would take time.

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Firstly, I would like to thank my supervisor, Professor Marco Neves, for the interest and enthusiasm with our research, even if at times things did not go according to plan and maintained an equally challenging and comprehensive posture. I could have not asked for a better person to not only guide me, but to push me to achieve more as a designer, a researcher and as a person.

To my father, Agostinho and to my mother, Ana Cristina, thank you for allowing me to fulfill my dreams and for all the sacrifices you have made to put me through my studies. Even though the last year was especially tough for us, I appreciate you with all my heart and I am the proudest son I could ever be. I love you.

To my two sisters Sofia & Lúcia, and my cousin Diana, thank you for taking me out of my desk and for distracting me these last few months, even if I was not up for it. To the rest of my family, thank you for believing in me.

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To my best friends, David, Gonçalo & Miguel, for more than 11 years of the greatest friendship that I could have ever imagined, for coming to my rescue in a blink without asking questions and for giving me the support I needed. To Irmandade, Andriy, Gonçalo & Hugo, I will forever be grateful for following me into the adventures I have put you up to, even if those were not our sanest or brightest moments.

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There is you in everything I do. Thank you.

Abstract

Interaction design is in transition, from the challenges of so-called user-centered design, into the immaterial concepts of ubiquitous computing and Internet of Things. This presents an opportunity for researchers and designers alike to explore different approaches and concepts with the integration with new technologies. With this in mind, we produced an exploratory study that focuses on pairing the emergent technologies of autonomous systems with print media. Additionally, this phase of Interaction Design has prompted an alternative approach to the field that focuses on materiality of interaction, fostering principles of tangible interaction and multimodality of interfaces. We developed a cognitive map to assess this research context, along with the tendencies of three waves of HCI, which provided insights into the present state of the field. Following that, we produced an analysis of the theoretical landscape surrounding tangible interaction. This provided us with knowledge and concepts to propose a TUI framework that sought to encompass previous lines of thought with emerging tendencies for material interaction. The literature review culminated in a characterization of print media and autonomous systems as materials for interaction design, although the research community has overlooked these two approaches as such. Finally, in a research through design approach, a methodology was produced to provide a guideline for researchers and designers alike to develop AI-enhanced interactive print devices. Through this process, we designed seven proposals that indicate potential opportunities in interaction in a print media and artificial intelligence environment.

Keywords: Interactive Print, Artificial Intelligence, Tangible Interaction, Materiality of Interaction, Research through Design.

Resumo

O design de interação encontra-se num momento de transição, dos desafios do design centrado no utilizador para os conceitos imateriais da Computação Ubíqua e da Internet das Coisas. Isto representa uma oportunidade para investigadores e designers explorarem abordagens e conceitos diferentes, juntamente com a integração de novas tecnologias. Assim, foi produzido um estudo exploratório focado na integração de sistemas autónomos com impressão interativa. Esta fase do HCI suscitou uma abordagem alternativa centrada na Materialidade da Interação, fomentando princípios da interação tangível e da multimodalidade das interfaces. Tendo isto em conta, foi produzido um mapa cognitivo para a análise do contexto em que esta investigação se insere, através das tendências das "três ondas do HCI" que forneceram insights sobre o estado atual da área. A partir dessa contextualização, produziu-se uma análise dos conceitos inerentes à investigação da interação tangível. Esta classificação forneceu ferramentas e ideias para propor um modelo de interfaces tangíveis com o intuito de envolver reflexões prévias com tendências emergentes de interação material. A revisão da literatura culminou na caracterização dos meios impressos e dos sistemas autónomos como materiais para o design de interação, embora a comunidade científica as tenha negligenciado como tal. Finalmente, numa pesquisa através do design, foi produzida uma metodologia para fornecer um guia de desenvolvimento para investigadores e designers produzirem dispositivos de impressão interativa aumentados por inteligência artificial. Através deste processo, os investigadores produziram propostas de design que indicam as potenciais oportunidades de interação num contexto de meios impressos interativos e inteligência artificial.

Palavras-chave: Meios Impressos Interativos, Inteligência Artificial, Interação Tangível, Materialidade da Interação, Investigação através do Design.

List of Acronyms and Abbreviations

HCI - Human-Computer Interaction

AI - Artificial Intelligence

ML - Machine Learning

IoT - Internet of Things

AR - Augmented Reality

RtD - Research through Design

GUI - Graphical User Interface

TUI - Tangible User Interface

Glossary

Internet of Things – Network of devices connected to the Internet which allows for the interconnectivity of all systems, for collecting and sharing data. (Rose et al., 2015)

Ubiquitous Computing – Concept in which computers are embedded on any device, location and time, interacting with social and physical environments. (Lyytinen & Yoo, 2002)

Autonomous Systems – Computational algorithms that allow for the creation of independent systems that learn through the collection of statistical data. (Gillies et al., 2016)

Augmented Reality - "A real-time direct or indirect view of a physical realworld environment that has been enhanced / augmented by adding virtual computergenerated information." (Carmigniani et al., 2011)

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Introduction

A. Context & Problematization

Digital manipulation has been at the forefront of most interaction design devices, given technological advances in the past decades, as smartphone devices and personal computers are greatly accessible. Alongside this exponential growth in hyperlink media, there has been a concern with exploring the future of interfaces for interaction design, mainly in the ubiquitous computing approach. As Artificial Intelligence (AI) has fostered promising Machine Learning (ML) algorithms, inclusion of these autonomous systems in interaction design has been of particular interest recently. The values of Industry 4.0 are very much so in the opportunities available for these approaches, but the output made by researchers has been underwhelming from an Interactive perspective. Also denoted as the Fourth Industrial Revolution, this shift is characterized by advancements in manufacturing through the introduction of “new technologies, including Internet of Things (IoT), cloud computing and analytics, and AI and ML into their production facilities and throughout their operations.” (IBM, n.d.). As demonstrated in Figure 1, the focus on interactive methods has been the least explored by researchers in the Industry 4.0 paradigm.

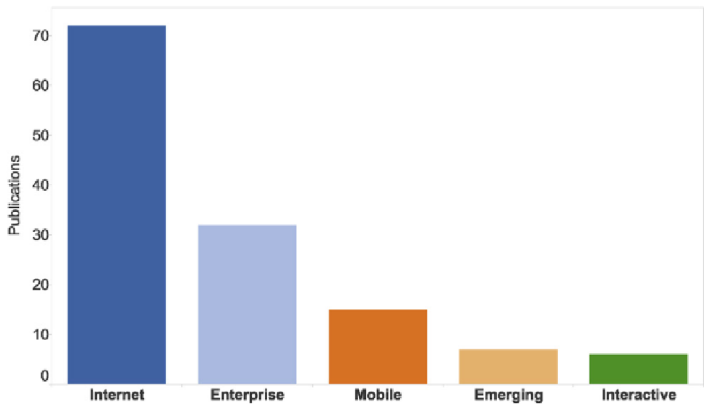

Fig. 1 – Classification of technology paradigms and methods in Industry 4.0. Source: O’Donovan et al. (2019).

Even though there have been breakthroughs in autonomous systems and digital interfaces, there are still impactful media for interaction design to tackle. Mainly, interactive print media, as it has become stale since its evolution to hyperlink media, as its interfaces have maintained the same level of interactivity, through a representation-driven design. Additionally, publications of both interactive print and tangible interaction have been put aside in the concerns of the research community regarding the Industry 4.0 context (Fig. 2).

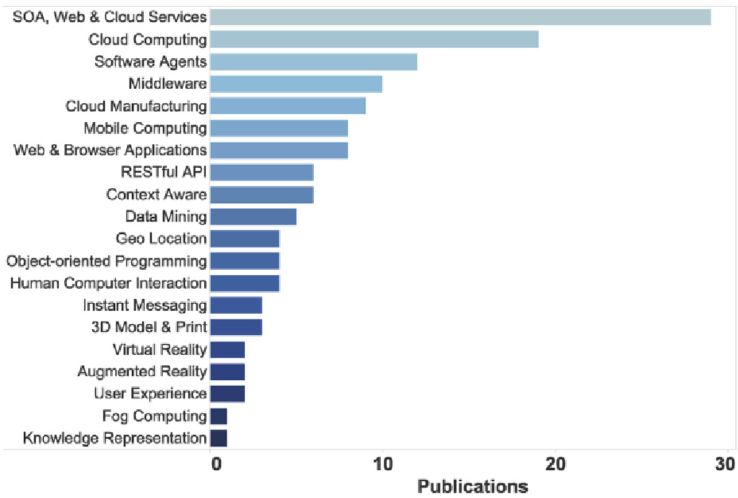

Fig. 2 – Distribution of technology paradigms and methods in Industry 4.0. Source: O'Donovan et al. (2019).

With this in mind, this document seeks to integrate the technologically advanced theories of ubiquitous computing, through autonomous systems, with the vastly unexplored interactive print and tangible interaction concepts. As autonomous systems deal with dynamic and digital information, bringing together these computational interactive materials with tangible static media can dictate possible future tendencies for interaction design. Not only that, but this document attempts to prompt the scientific community to gradually improve the quantity of research produced with this concern in mind.

B. Research Questions

Q1. How does interactive print, autonomous systems and materiality of interaction fit in relation to each other in the third wave of HCI?

Q1.1. How has tangible interaction been framed in past research and what is the tendency moving forward?

Q2. How can print media be designed as interactive artifacts when influenced or benefited by autonomous systems?

Q2.1. How can the material-centered approach define a research through design methodology for AI-enhanced interactive print artifacts?

B. Research Goals

G1. Congregate the characteristics and properties of the main research topics to find connections, tendencies, and complementary natures of each.

G1.1. Produce a cognitive map to explore and outline how HCI has evolved and to acknowledge opportunities for possible interactions.

G1.2. Produce a framework to assemble concepts and goals in past research of tangible interaction.

G2. Seek out a research through design process to assess the possibilities of integrating interactive print with autonomous systems.

G2.1. Assess the tendencies of development for the defined proposals in an iterative process.

G2.2. Produce design guidelines for developing AI-enhanced interactive print artifacts.

C. Hypothesis

The aforementioned lack of contemporary research in the interactive print context, especially when paired with autonomous systems, provides researchers with the opportunity to address the possibilities in this premise. The materials that make the producing interfaces in this nature possible are definitive to the conceptualization of interactive devices, so the comprehension of the properties of those materials is crucial to the development of interfaces.

This understanding of materials is in line with a material-centered approach that has recently been proposed by researchers, as materials are seen as the groundwork for the production of interactive systems.

As for the conceptual approach in this research, the tangible interaction method of pairing digital and physical natures of interfaces is relevant given the materials that are being addressed.

Given the focus on producing research output in this context, we opted for a research through design methodology for the development of design proposals that explore the possibilities in the AI-enhanced interactive context.

Therefore, **the production of research through design in AI-enhanced interactive print devices, allows for the exploration of yet to be seen possibilities of interaction, that are centered around the opportunities provided by the characteristics of the design materials, inherent to this proposition.**

D. Research Design

For the development of the hypothesis, the methodology associated with a project of the kind presented is composed of a group of methods that complement each other both in theory and in practice. Thus, using a mixed methodology, it is believed that through theoretical and conceptual research the authors have the tools to produce relevant insights in the practical aspects of design. This also promotes a bigger complementary nature throughout this research, as both approaches lead to the same goal. Considering that this is a work in the interaction design field, we assumed an interventionist methodology, as the design proposals that will be developed are expected to have an impact on the scientific community.

First, a literature review allowed to build our research hypothesis, inherently related to case studies, and also enabling the development of the proposed framework. Additionally, producing a cognitive map allowed for the contextualization of the relations between research topics, both organizing and complementing the diagram of theoretical background.

In a generative phase, through information obtained in previous stages, and with formulation of a hypothesis, an iterative research through design development process was established, influenced by the material-centered interaction design approach. In this phase, we present a series of project concepts with various levels of development, as a way to denote the quantity of interaction possibilities in this research context. Thus, starting this process with sketching, interactions to be carried out and the physical manifestation of interfaces become the basis of the entire outcome.

Subsequently, our proposals carried out a similar iterative process, in which development tendencies can be identified to denote how each idea came to fruition, allowing for a thorough analysis and conclusion making.

Finally, through this creative process, conclusions were identified that made possible to revisit the hypothesis, allowing for a reflection of the investigation, and assessing relevancy of this document. A synthesis of the overall research plan can be seen in Figure 3.

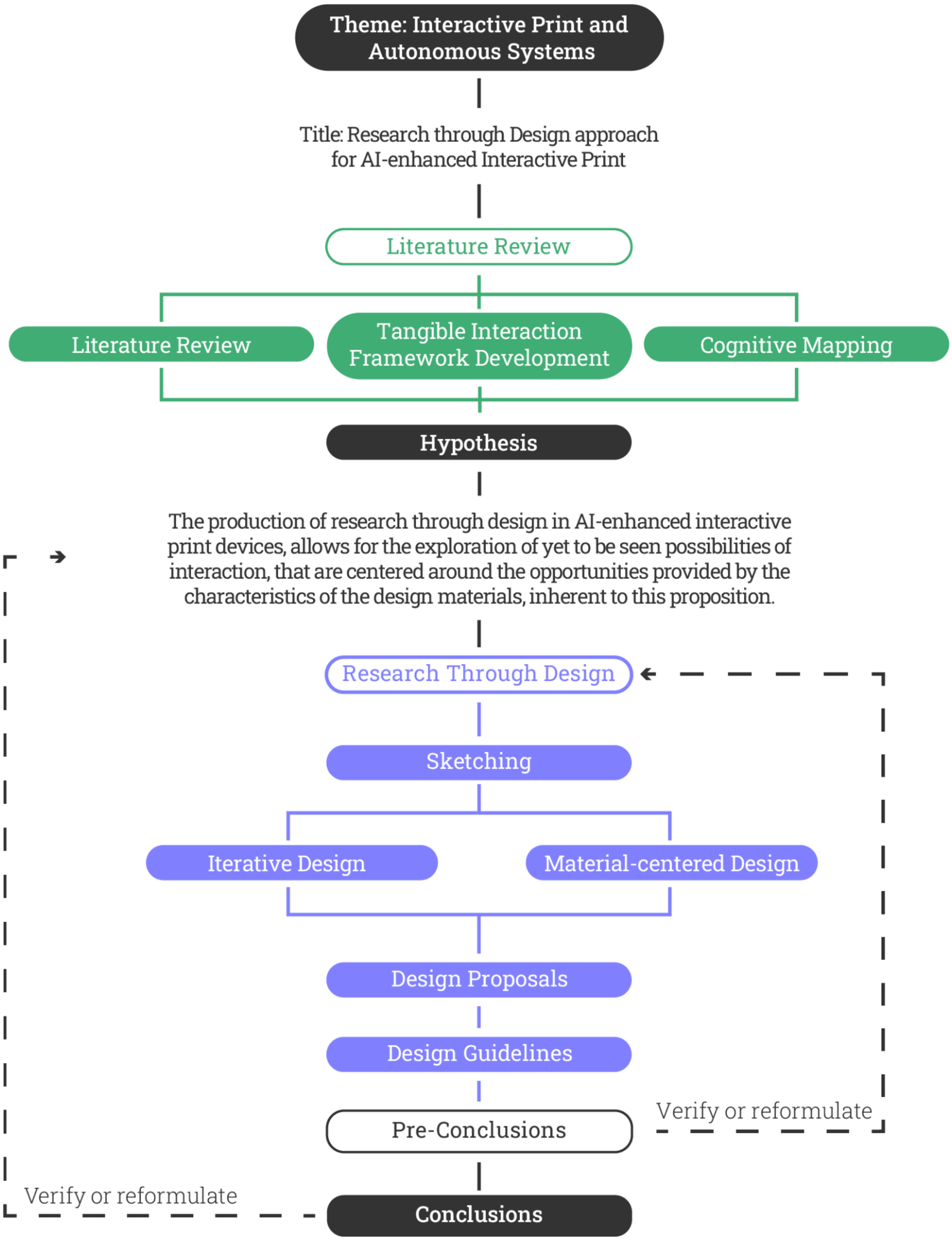

Fig. 3 – Research Organogram.

E. Dissertation Guide

This document is composed of an introduction, four chapters and a conclusion.

The introduction presents the context in which this research includes itself, as well as its problematization, followed by the research questions and research goals, finalized by the research design and organogram.

Chapter 1 is focused on contextualizing the research topics, in line with the three waves of Human-Computer Interaction (HCI) (Bødker, 2015), through the development of a cognitive map. Furthermore, the concept of material-centered interaction design is presented and defined, as well as how it fits in the contemporary tendencies of the field (Wiberg, 2018).

Chapter 2 is dedicated to the tangible interaction scope, as we address the past and present trends of the practice and how it can evolve in future research. Additionally, there is a descriptive analysis of Tangible User Interfaces (TUIs) frameworking, as there is an attempt to encompass the perspective of numerous authors in a proposed framework, the M-TUI model.

Chapter 3 is centered around the main interaction design materials of this research, interactive print and autonomous systems, as the authors assess the current state of the research on both topics. Moreover, this chapter attempts to promote connections between the two, taking into account their complementary natures while maintaining focus on interaction.

Chapter 4 details a research through design methodology that we developed to produce interaction design proposals regarding the AI-enhanced interactive print context. The iterative design process of development is also described thoroughly, producing insights on the ideation and production of each proposal.

Finally, the conclusion contains the discussion of the research goals, the implications of the thesis, as well as considerations regarding future studies and dissemination of the research.

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Chapter 1. Contextualizing Research Topics

Ever since Bill Moggridge and Bill Verplank introduced us to the term 'interaction design' in the 1980s, this area of creation has increased exponentially in such a way that nowadays, it is difficult to not come in contact with it. From the Xerox Star in 1981 (Verplank, 1989) to the incredibly complex but common smartphones, interaction design has taken immense strides in technological and digital fronts. But interaction design is not just its media or interface, it is about understanding behaviors and considering the various dimensions that constitute interaction in our lives (Moggridge, 2007). With experts in this area such as Donald Norman (2013) and Jakob Nielsen (1994) producing works in cognitive psychology, usability, and user experience fields, it was possible to understand that interaction focuses on much more than the interface itself. In this dissertation, the research context composed of concepts regarding interactive print, autonomous systems and materiality of interaction present an opportunity to complement and promote a definition of relations between each of them (Fig. 4). As the interaction design scope is broadening at a fast pace as the connections that can be made of each approach will provide insightful outputs as to what are the present tendencies for the field and how its future could be predicted. This is particularly evident in the three waves of HCI (Bødker, 2015), as this research topic is explored in the following section, to contextualize the tendencies of interaction design since its initial manifestations. Regarding the relations between interaction through print media and autonomous systems, this document sought to comprehend the context in which those fields are integrated. Additionally, this section provides a groundwork for the following phases of Research through Design (RtD) as it is explored in a way that allowed us to produce a congregation of innovative possibilities of interaction.

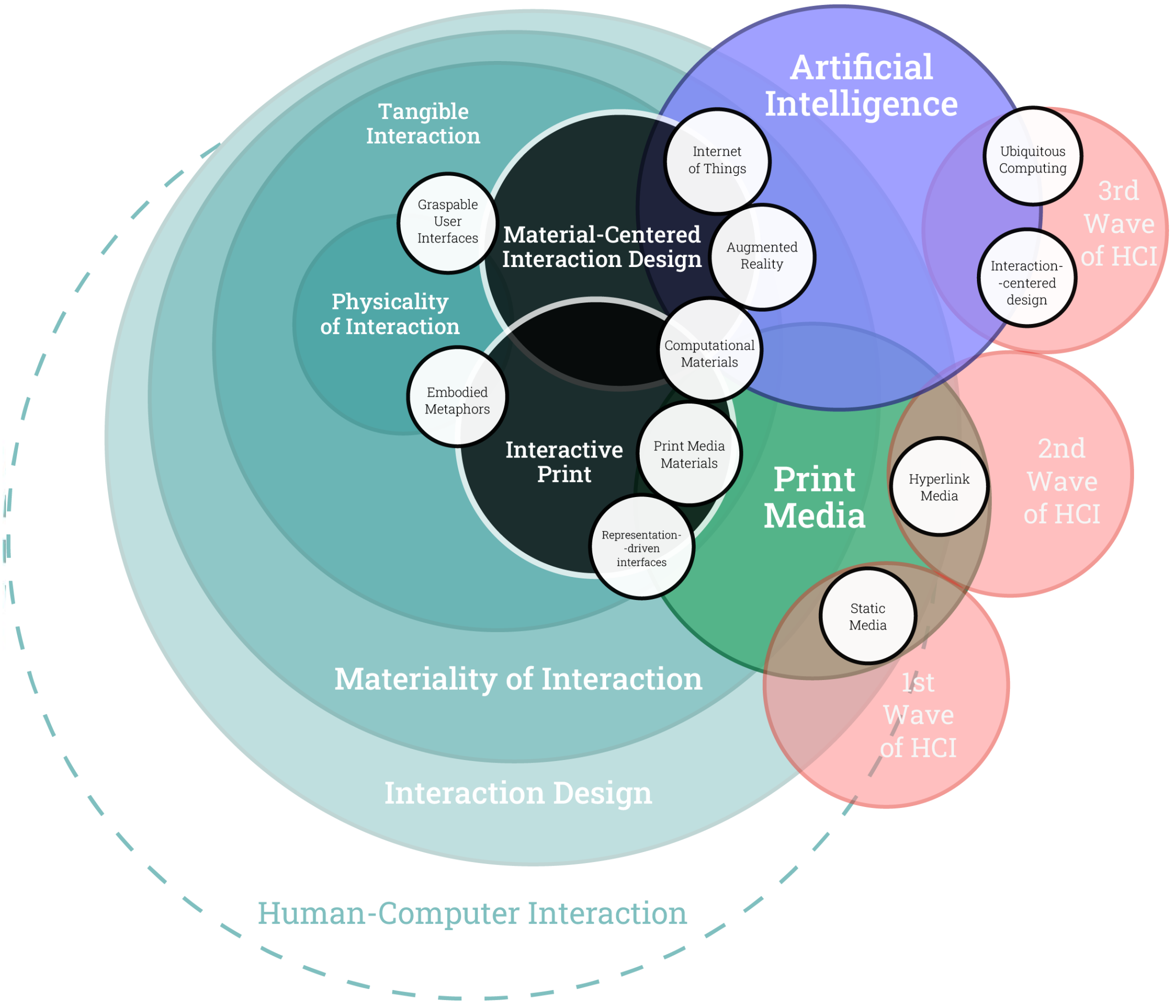

Fig. 4 – Diagram of Theoretical Background.

1. Cognitive Mapping

A. Methodology

To visually represent the conceptual relations between the research topics in which this document is focused, cognitive mapping is a tool that can produce a concise and clear representation of that context, even before the literature review process. As per Swan (1997): "In psychology, 'cognitive map' was a term that was developed to describe an individual's internal mental representation of the concepts and relations among concepts" (P. 188). This definition can also apply to domains such as design, as it promotes a broader perspective on the research topics and its context. Not only from a problem-solving point of view, as cognitive mapping can also deepen the understanding of the researchers through a dynamic thought process. Kearny & Kaplan (1997) take a psychology-sided approach, in saying that cognitive mapping is an evaluation tool of people's "assumptions, beliefs, "facts", and misconceptions about the world" (P. 580). This assessment allows for psychologists to assess the way that certain concepts are seen and thought of, especially knowledge that is contradictory to someone's depiction of reality, as those tend to ignore or refute it. Relations like these can go from "proximity (A is close to B), similarity (A is similar to B), cause-effect (A causes B), category (A is a subset to B) and contiguity (A follows B)" (Swan, 1997, P. 188). All these sets of relations can prove to be a design challenge, especially in more complex maps, as not all of them can be represented through a line in-between concepts. Ackermann et al., (2004) use cognitive mapping as a way to improve the information that is gathered in interviews for problem-solving purposes, as the interviewees participate, certain details and recurring phrases allow for the development of a map of relations. Although there are many methods for gathering knowledge to create a cognitive map, mostly through analyzing the mental models of patients or interviewees (Swan, 1997), that was not the case for this particular subject. As our literature review had such a commitment to research the relations between keywords and research topics, that output is more than enough to materialize a cognitive map. Even though the processes differed in the origin of the theoretical material, the following steps for development were similar to those used by Swam (1997); Ackermann et al. (2004); Lourdel et al. (2007). Lourdel et al. (2007), when tackling sustainable development issues with students, firstly produced a simple cognitive map that allowed students to better visualize straight-forward relations between concepts. Both Ackermann et. al (2004) and Lourdel et. al (2007) chose to have on the first few steps to be categorization, as that is going to influence the whole structure of the map, mainly creating hierarchization between words or phrases, even before creating a relation between them. From a representation standpoint, categories can be identified through colors, sizes and position, therefore creating boundaries for the map to exist in. One of the limitations of this method, when applied to a certain group of people, is that it needs to be taken into account the level of expertise that group possesses about the subject (Lourdel et. al 2007; Swan, 1997). From the initial categorization of research topics, Ackermann et. al (2004), collect a series of phrases that need to be translated from a text format, into mapping content. So, the process in this phase was similar in the development of the cognitive map regarding our literature review, as a number of phrases and words that expressed the research goals were gathered into topics:

- **Establish connection between interaction design (as shaping of physical/digital, updatable systems), with print media.**
- **Understood as communication and knowledge materials, subject to creative action.**
- **Interaction design is dealing with developments allowed by new technology. From GUIs to Ubiquitous Systems and from Programming to AI.**

- **Interaction design should recognize its material object as a physical and digital hybrid, as a symbiosis.**
- **From representations to tangibility.**
- **The design of print media.**
- **Print media contributes to knowledge acquisition, daily tasks, content distribution, mobility and should foster critical thinking.**
- **Print media is characterized by its graphic elements and it lacks an approach to behavior and dynamic information.**
- **Autonomous systems based on AI and ML introduce dynamic and growing information which may contradict such predictability.**

Then, more specific terms were gathered from the collection of phrases that would simplify the organization of the map as topics and subtopics. As the main goal of the research is to explore how interactive print can move forward with integration of AI and ML, Print Media and Interaction Design were distinctively the main concepts of the map, located on opposite sides. Simultaneously, several other subtopics were introduced on the grid, categorized by proximity with the two aforementioned terms (Fig. 5). Some concepts were inherently connected to their "parent" concepts, for instance, "Interaction Design" and "Technology" had to maintain a close proximity, but others had to be placed in the middle, as they can be influenced by both sides of the map, or not having a particular necessity of being close to any other subtopic, such as "Predictability".

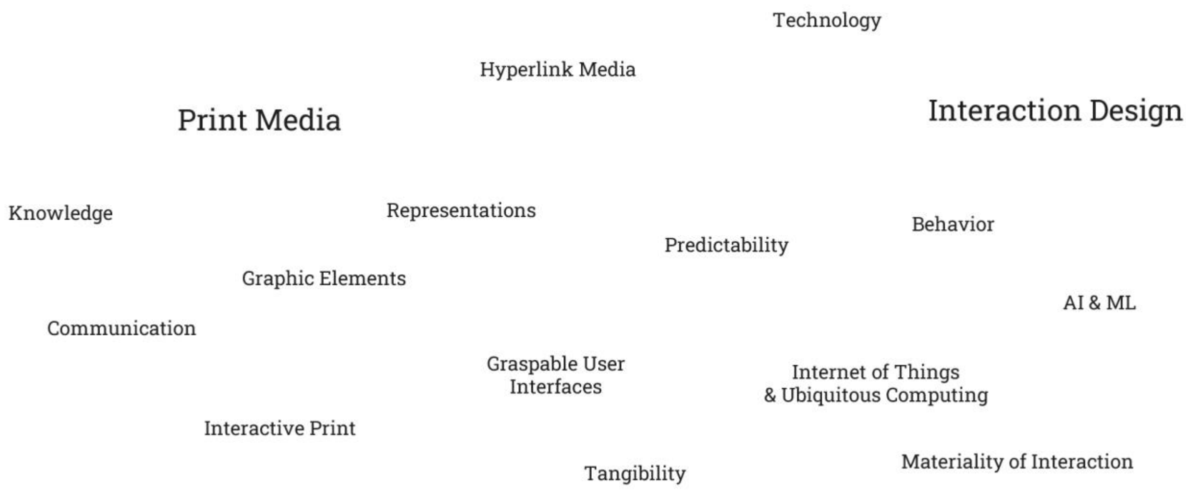

Fig. 5 – Initial structure for cognitive map.

With the defined initial structure of the map, as both Ackermann et. al (2004) and Lourdel et. al (2007) infer, the next step is to create relations between the terms/phrases. This means that arrows can start to be created between concepts and its hierarchization. For example, an arrow with a large stroke can represent a strong relation, i.e. cause-effect, while a slimmer arrow could merely mean a proximity between ideas (Fig. 6).

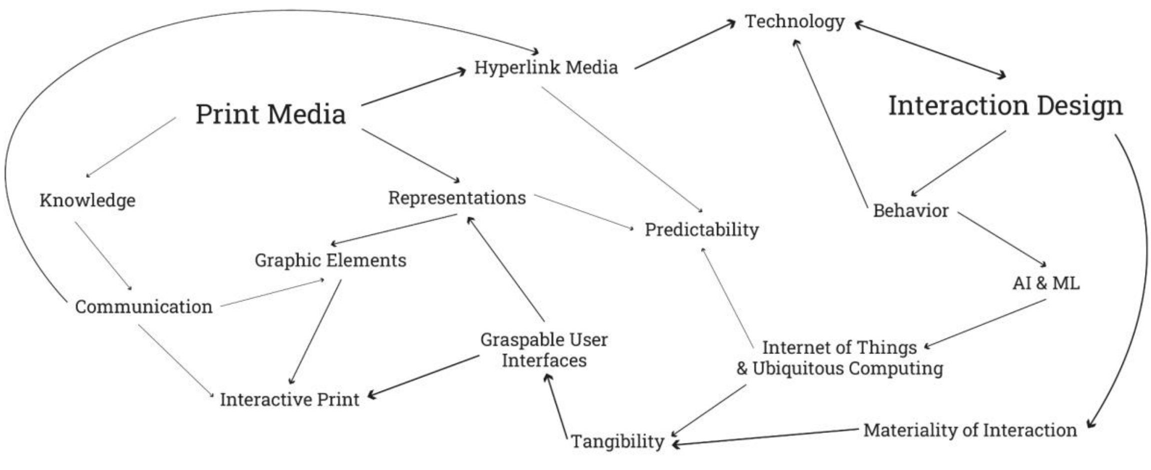

Fig. 6 – Linear relations for initial structure.

With the linear affiliations produced, there was still ambiguity with regards as to what the arrows represented, as mentioned above. So, the connections between topics had to be better explained and that would allow the whole map to undergo another iterative phase, as some relations would not make sense in a specific location, or there needed to be a stronger connection that better represented the influence of a concept on another (Fig. 7).

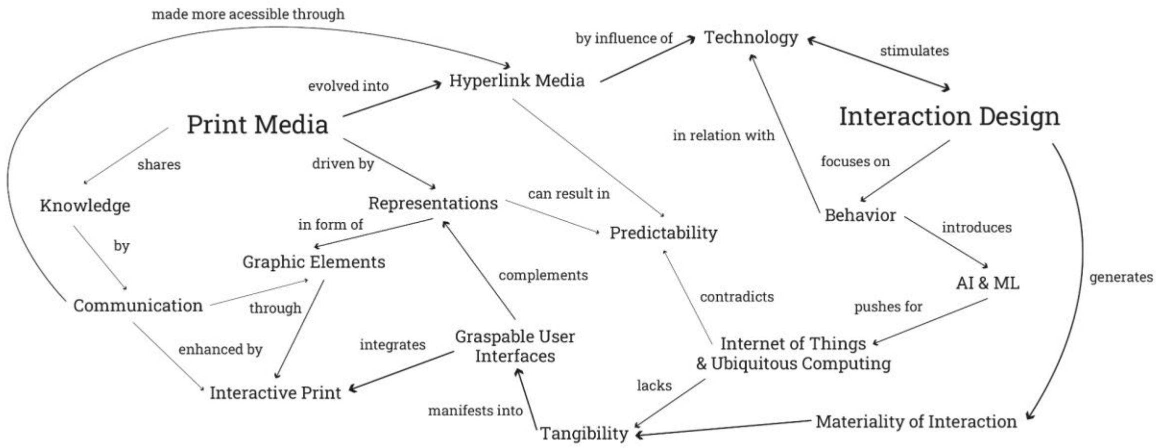

Fig. 7 – Addition of labels to relations.

Now that the overall structure and relations of the map were defined, an overhaul of the visual representation of the map was made to better organize the relations in orthogonal directions. This modification improved the appearance of the map as well as better defining the hierarchy in concepts and their respective relations. An additional concern was the introduction of three waves of HCI in complement to the already defined terms and relations, adding a temporal hierarchy to the cognitive map. So, simultaneously with the reorganization of the map, three different colored layers were used to represent each wave of HCI, which could work as individual modules when assessing the information. As the literature review matured throughout the development of the map, final additions were made to complement the already existing concepts and relations between them (Fig. 8).

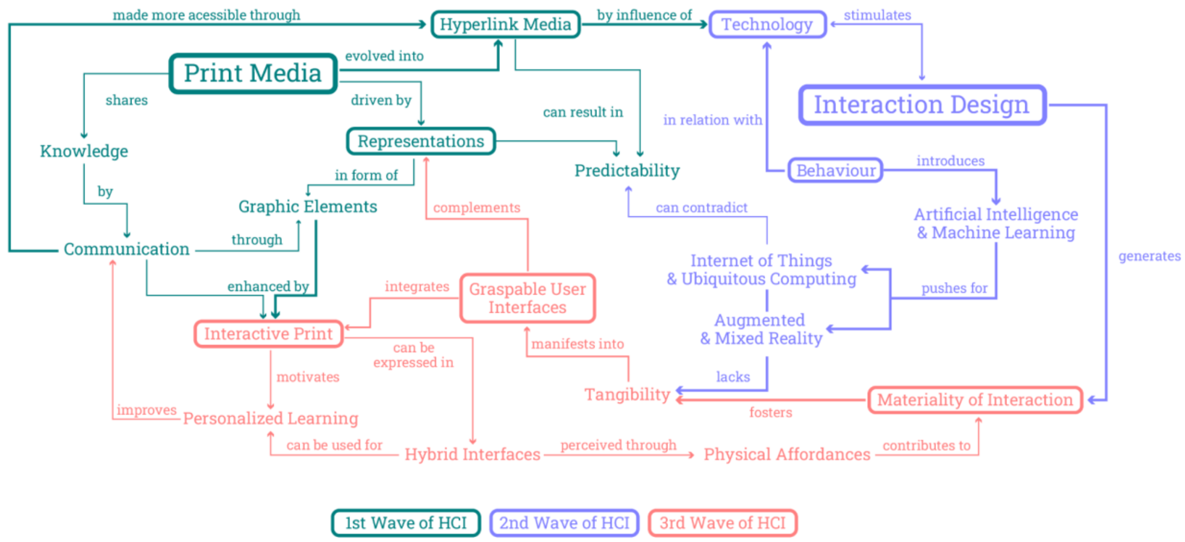

Fig. 8 – Final iteration of the cognitive map..

B. Contextualization

Print media is one of the most recognizable media for knowledge sharing over the years, and although there have been great technological advances in recent decades, its characteristics have not changed with it (Fig. 9). Hyperlink media has brought a new dimension to advertisement, to social networking and journalism, but static media has not followed in innovation. The tendency for updating static media to an augmented state was to create digital versions of it: books became e-books, printed newspapers became websites and so on (Al-Imamy, 2020). This is mostly correspondent of a very early phase of the 2nd wave of HCI, in which the focus is user-centered design, making such knowledge available to all users, through digital interfaces (Bødker, 2015). This form of communication is also thought of as a representation-driven focused approach, in which the metaphors used represent real world interactions and behaviors. Wiberg & Robles (2010) believe that although this was the norm for most digital interfaces created in recent years, it also distanced the user from the material world and therefore the interaction became devalued as the digital device gained prominence.

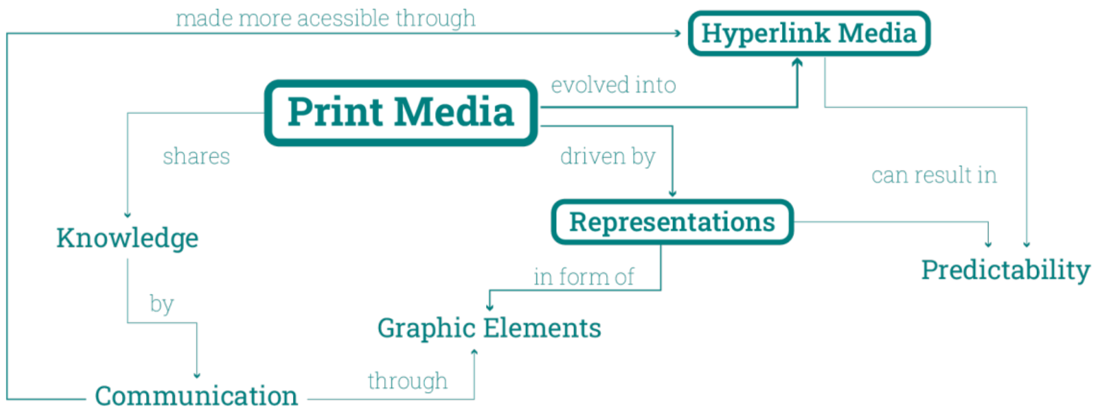

Fig. 9 – Cognitive Mapping, 1st wave of HCI.

Print media still has its advantages, especially when it comes to enhancing education as the main issue using digital media for education is the cognitive load that comes with that interface (Lai et al., 2019). Simultaneous evolution of technology and interaction design has also created a path to enhance traditional print media (Fig. 10). Advances in Augmented Reality (AR) fostered both educators, engineers, and designers alike to add a new dimension to static media, to better express the learning subjects (Kazanidis & Pellas, 2019). Kazanidis & Pellas (2019) also add that AR has proven to be a successful interface when integrated within classrooms, regarding both motivation and participation, and results when it comes to teaching and learning results. Majeed & Ali (2020) corroborate this conclusion as values of interaction design are introduced into an educational environment, mostly user-experience related concepts. Interactive print interfaces are now sought out for various subjects and for different levels of education given its versatility and immersion, as well as its positive impact on the learning experience of students (Nadolny, 2017). One other main point for introducing AR in an interactive print media, is personalization, as both students and teachers can access information to their preference and needs (Li et al., 2021). In line with this, the emergence of AI and ML has provided several possibilities when it comes to improving interactive print interfaces. AI is not introduced in this context just for the betterment of personalization and education, but to also increase the effectiveness of the markers that are increasingly inconspicuous and accessible. The convergence of both AR and AI advances have made considerable interaction design possibilities seem accessible, either regarding educational systems or any other context when allied with interactive print.

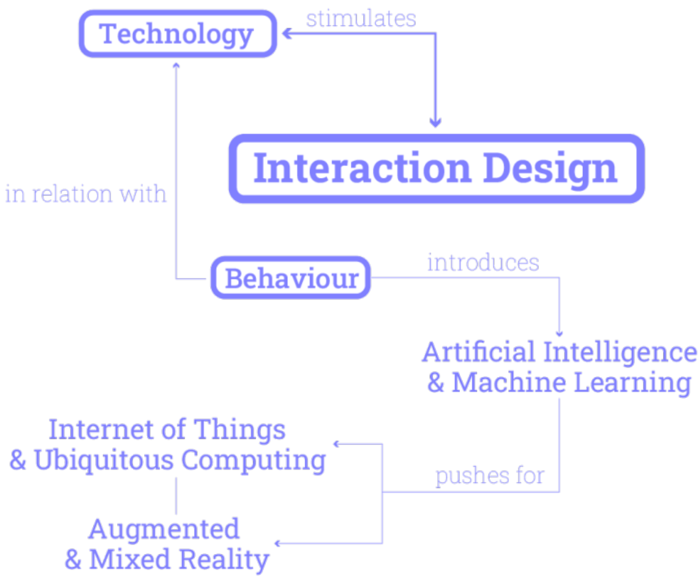

Fig. 10 – Cognitive Mapping, 2nd wave of HCI.

The tendency for interaction design devices should be to increasingly add tangibility to interfaces (Fishkin, 2004), especially given that the concepts of IoT and Ubiquitous Computing (Weiser, 1991) have been regarded as the future of interaction design (Wiberg, 2018). These "3rd wave of HCI" systems expressed in Figure 11 depend on complex computing devices and are characterized as somewhat intangible, such as cloud services, because although the user does not perceive its origin, they still interact with them through material interfaces. This is also in line with what Wiberg (2018) denominates as "Compositional Material Interaction Design" in which the focus is to add depth to the interaction in relation to already previously design-focused computers (1st wave of HCI) and humans (2nd wave of HCI). This materiality can be expressed by using technologies such as AR and AI as materials in a way to expand the focus in interaction, inside the HCI field. This broadening of an interaction-focused design can also improve the previously mentioned capabilities of integrating print media with a 3rd wave of HCI interface.

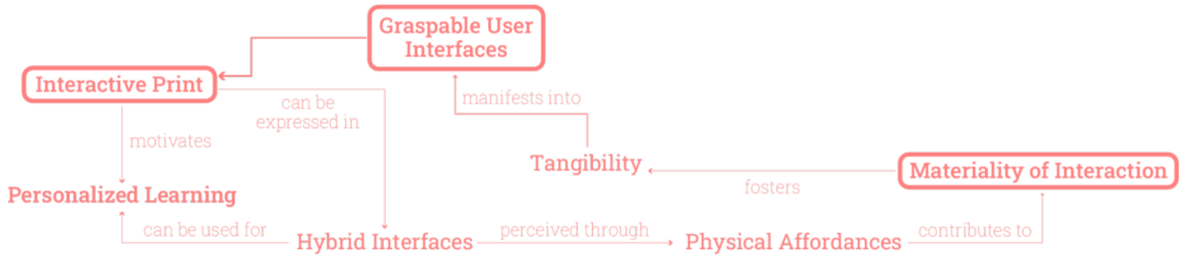

Fig. 11 – Cognitive Mapping, 3rd wave of HCI.

2. Materiality of Interaction

2.1. Three Waves of HCI

A. The user as a tool

In the early years of computing, “the human is often reduced to being another system component with certain characteristics, such as limited attention span, faulty memory, etc. that need to be factored into the design equation for the overall human-machine system.” (Bannon, 1995, p. 206). In this first wave of HCI, the focus was “on the human being as a subject to be studied through rigid guidelines, formal methods, and systematic testing.” (Bødker, 2015, p.1) representing the designer’s point of view regarding the HCI practice, the users were mere tools. Bannon first-hand witnessed the beginnings of user-interface design but in which there was not any type of user-research, and not only it was not thought of by companies, but it was also entirely disallowed. This meant that through the vast majority of the first wave of HCI design, users were seen as an external factor to the machine, when they are an integral part of the interaction. The designer’s perspective of engaging users stemmed from giving knowledge of operation of the computer through sets of complex instructions of coding and systemic processes (Carroll and Mazur, 1986). Carroll and Mazur give the example of the Apple Lisa, a computer system for personal and professional use that had an incorporated online tutor, or as we would call it nowadays: a virtual assistant. For Bannon, the shift began when the human stopped being considered an “idiot” and became to be reckoned as “naïve”. Although it might seem to be a slightly irrelevant change of appraisal, user interfaces quickly adapted to this concept and the industry started developing the first “user-friendly” interfaces. But this deviation from the “user as a tool” idea did not come from the designers and engineers of said computing machines, it started when HCI was not only about human-machine interaction but became a larger domain for understanding human cognition (Carroll and Campbell, 1989). This originated the studies of Donald Norman (2013) and other cognitive psychologists that would change the model in which HCI practice and research were produced, marking the beginning of second wave HCI. The outlook on the three waves of HCI is denoted on Figure 12.

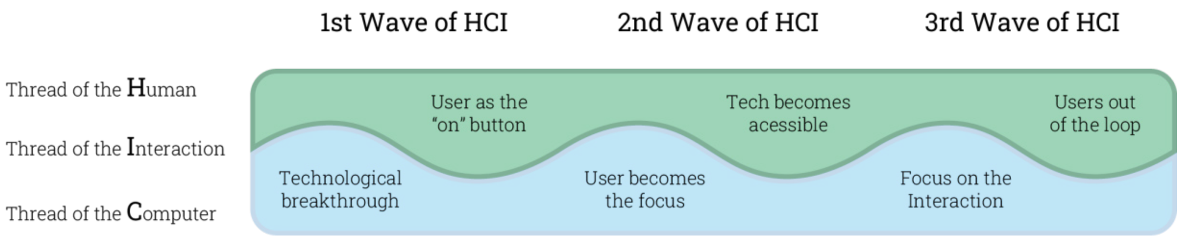

Fig. 12 – Three Waves of HCI. Source: Bødker (2006).

B. User-centered design

From the user being seen as an inactive part of the HCI definition in the first wave, it becomes a central part in the practice and research of the subject (Bødker, 2015). User-centered, human-center, user friendly, usability and user experience are all concepts that regard the human being as the most important aspect of the whole interaction. Those same characteristics are placed on the machine, not on the user's responsibility or availability to learn and understand, contrasting with the first wave production objectives. Although we acknowledge the relevancy and impact of these concepts (Norman, 2013 and Nielsen, 1994) for the field, this section is focused on the contextualization of the changes in interfaces in a broader spectrum, over the generations of HCI research. As Bødker (2006) assesses, the second wave of HCI is characterized by multimodal interaction, that although the focus shifted to the desktop computer, the workspace around it still has an influence in the interface. This is particularly relevant both in skeuomorphic design principles that sought to "borrow (...) properties, look, and feel from similar objects in the physical world." (Wiberg, 2018, P. 177) as well as with representation-driven interface design. These two concepts meant that gradually the desktop computer would assimilate all the work functions of a physical desk (Bødker, 2006). "Ten years later", as Bødker (2015) describes it, not only that thought came to fruition, but so many advances in technology made it so that all those functionalities present in an office computer would be assimilated in a particular smartphone. This also marks a big shift in from a market approach, as it was thought that the focus for innovation a decade ago would be on work-related contexts, but it has gradually become "life-related" (Bødker, 2015). The accessibility of highly functional technology combined with UX and UI studies that promoted a more lenient learning curve, meant that users became very-well acquainted with how these devices and how they could be improved. This introduced the participatory design concept, in which users can have a direct impact on the development of future interfaces and systems (Schuler & Namioka, 1993). This is a contradictory approach to what the 1^{st} wave HCI was known for, which was to produce devices in which the users were merely tools, and have, since then, had a say in how those same devices are designed. Integration of technology in everyday life has become increasingly seamless with all sorts of artifacts gaining a digital functionality that allow users to control their computer behavior with ease, from fridges and thermostats, to lighting and audio equipment, for example. This is the start of the 3^{rd} wave of HCI concepts of IoT and Ubiquitous Computing, in which everything in our daily lives is connected through technology, allowing the easiest access of every detail of the linked devices (Bødker & Klokmose, 2016). Although this is very appealing from a user standpoint, seemingly making life much more efficient, there comes a few challenges for third wave designers and researchers when focusing on interaction instead of technology (1^{st} wave) or the user (2^{nd} wave).

C. Interaction-centered design

Bødker (2015) describes third wave HCI as being mostly focused on artifact ecologies. This concept is brought by the acknowledgment that "users' shared capacities and experiences are not just based on individual acting and learning in the world; rather, they are bound to shared practices" (Bødker, 2015, P.27), because group of artifacts that accompany our everyday lives have an impact on the outcome of such activities. As these artifact ecologies expand, research now turns into how individual artifacts and materials communicate with each other, so that the whole experience is uniform throughout the interfaces. Harrison et al. (2007) do not approach this evolution of HCI as "waves" but believe there are three paradigms that coexist in this field, specifically for this third wave, described as "Third/Phenomenologically-Situated Paradigm" (2007, P.1). Harrison et al. (2007) value the impact that ubiquitous computing has had in this phase of HCI research, as it has brought into light a new complexity to the HCI context. Fallman (2011) adds another point of view by conveying that "At the same time, a range of new pervasive technologies, (…) are enabling this rich array of digital artifacts to communicate with each other, to create ad-hoc networks, negotiating handshakes, and exchanging information, while leaving us—formerly known as users—outside the loop altogether." (2011, P.1) Fallman also finds it difficult to separate a user experience regarding HCI, or if it is just "any other kind of experience" (2011, P.1). Bødker & Klokmose (2016) go further in this concern and try to identify the multiplicities of experiences in the aforementioned artifact ecology, as there is a conceptual and behavior distinction between physical and digital interfaces. Additionally, the authors address the possibility of combining interactions, in a blended environment, in which users can connect with several types of interfaces, without losing track of the interaction. In this context, researchers (Fishkin, 2004 and Robles & Wiberg, 2010) are pushing for a "material turn" in which all these digitized interactions can have a physical component that is primarily focused on the interaction and the interface, through material manifestations. This centralization of the Interaction on the HCI scope is described as "interaction-centered design" (Fig. 13) or "interaction-first principle", as labeled by Wiberg (2018), aiming to mature its materiality in the increasingly invisible interfaces. Rosinski & Squire (2009), strengthen the interaction-centered approach, by arguing that although understanding human behavior in relation with the computer, the interaction aspect of the composition needs to have a focal importance in the development of an interface.

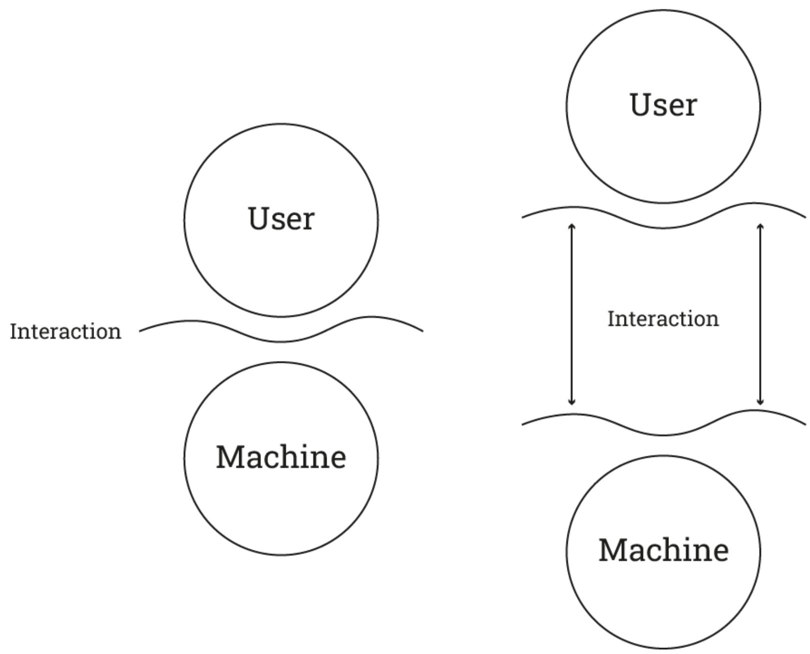

Fig. 13 – Interaction-centered design.

2.2. Material-centered design

As Mikael Wiberg (2018) expresses, there is a "contemporary trend in interaction design toward material interactions", as it is not uncommon to look at interaction design and immediately think about IoT or smart devices, but the author believes the focus of interaction is not on its media. Wiberg argues that interaction design is about the composition of materials coming together to form these interactive devices, through our creativity to reimagine these in different contexts and with different objectives. This is corroborated by Robles & Wiberg (2010) and Fishkin (2004), in that more and more interfaces will begin to have a bigger focus on tangibility in future years. This also comes simultaneously with the challenges of the third wave of HCI (Bødker, 2006), in which we will see a bigger development of systems based on IoT and Ubiquitous Computing.

A. Understanding materials

In a generation of interfaces based on metaphors, representation-driven systems and devices have been the norm since the 1980s and 1990s (Sharp et al., 2019). The well-known metaphors of the "desktop" and the "trash can" are staples of this central focus on the metaphors in interaction design. With the conceptualization of these main entities, the adjacent components started to derive from them, such as the "click and drag" allowed users to easily interact with said entities. This thought process guided users to understand how the structure of a complex device like a home computer or even the "cloud", as Wiberg (2018) exemplifies. Further on, it changes the whole perspective of said interfaces through the choices of metaphors. To address this process of distancing the user from the real-world entities to the metaphors, Wiberg and Robles (2010) call for a "material turn" as a way to add texture to a field in which the digital is the most common approach for interface design. The purpose of this is not to distinguish or separate digital and physical approaches, but to bridge the gap between both, as Ishii & Ullmer (1997) have called for. Ishii & Ullmer (1997) are not only referring to a manifestation point-of-view, but rather about a conceptual model in which contexts and projects can be looked at with a different set of “material lens”, as Wiberg (2018) denotes it. Hallnäs & Redström also address this shift, as they believe that “The designed ‘thing’ is material we use to build the acts that define its use or an instrument we use to perform these acts.” (2006, P.23). This thought process allows for interaction designers to expand beyond the traditional media and seek different approaches to an ever-evolving field. This is particularly important with the emergence of “artifact ecologies” (Bødker, 2015) rapidly becoming a reality rather than a speculative idea, and the interaction is no longer dependent on its media, as is the case for ubiquitous computing. With the accessibility of present computers, designers and researchers have looked at traditional materials such as wood, clay, even ice (Robles & Wiberg, 2011) and soap bubbles (Döring et al., 2012) to enhance interaction design. As digital materials are characterized as being dynamic, analog materials possess equal opportunities of producing changes in properties such as scale, shape, color, or even state of matter (i.e. water can easily become ice or vapor). Brownell (2005) produced a catalog of materials categorized from high-performance materials such as concrete and steel beams for construction, to repurposed objects that used all sorts of waste to produce different outcomes. One of these objects is the “Watercone” (Brownell 2005, P. 97), developed by Stephan Augustin, that is merely composed of a transparent plastic cone that purifies water through sunlight. With the condensation from the heat, the water purifies itself and expels the bacteria through the open top of the cone, exemplifying one of the aforementioned dynamic behaviors of simple materials, in this case plastic, water and light. Materials such as these have always had sensitive qualities when subject to different situations and including them in an HCI context will enrich both the capabilities of said materials, as well as pushing metaphor and representation-driven systems to have another dimension (Wiberg & Robles, 2010). The authors express that "Borders between surfaces and interfaces are blurring, sometimes disappearing completely, and creating new experiences of the built environment as crafted from computational materials." (Wiberg & Robles, 2010, P. 139), as one of the conceptual consequences of the material turn. Another objective of the proposal for a material turn is to shift from a representation-driven context, based on metaphors, to a material-centered interaction design, in which interfaces are no longer necessarily bound to a "box", as digital interfaces tend to be represented in a screen. This allows for a transition in which computing can take any shape and adapt to almost any surface, presenting material-centered interaction design as a tool for interfaces that are based on ubiquitous computing (Hallnäs & Redström, 2002). This will, once again, bridge the gap between digital computing and physical manifestations of materials, bringing both approaches together. Although, when designing and producing material-centered interaction design, there needs to be an educated understanding of the distinct characteristics belonging to both digital and analog materials. Through Wiberg's (2018) research, it is very challenging to produce interaction design without materials, as an interaction requires materiality to exist and be represented, even in contexts such as the 3rd wave of HCI, as devices are increasingly becoming digitized.

B. Forms, expressions & behaviors

Although conceptually the distinction between digital and traditional materials began to dissolve, in interaction design practices, especially related to the challenges of 2nd wave of HCI, the gap is still recognizable. Jung & Stolterman (2012) address the issues with the increasingly lack of physical interaction that is being replaced by digital materials, as the latter has improved user-centered design performance mechanics, but at the expense of material form giving and aesthetics. The authors attribute this shift in interaction design to a lack of theoretical and methodological research regarding the materiality in interaction design. Not only that, but materiality can pose as the bridge between the "formless" and lack of use of materials' properties and the dynamic and expansive scope of a computational system. Vallgårda & Redström (2007) introduce computers as an interaction design material and argue that it is not exclusively centered in metaphors, and "address issues related to misconceptions about computations being almost 'immaterial'" (2007, P.2). Redström inquires "(...) what happens if we try to think of 'technology' in terms of 'form' and 'material'?" (2005, P. 48) as he argues, on one hand, that physical materials such as wood and textiles have specific characteristics that are commonly known, such as textures, smoothness, colors and so on. On the other hand, there is the argument that digital and computational materials also have their own set of qualities but are not acknowledged as they tend to be hidden to better express "technological perfection" (Redström, 2005). So, even if to the clients, the computational materials behind a smartphone are very well blended with the cover and screens, when a designer is faced with a material-centered approach, all of the components need to be taken into account, as these influences the well-functioning of the devices. As Redström (2005) exemplifies, changes in telecommunication coverage can be seen as "immaterial" as it is influenced by the conditions of the outside environment, but the materials inside electrical components are physically reacting to these same conditions, resulting in very different technological expressions. These expressions have an origin on the function side of devices, in their integrated microcontrollers, and are usually expressed through form, by visual or auditory feedback for example. From an industrial design point of view, Djajadiningrat et al. (2004) argue that there is a distinction between appearance and action, as they also address the tendency for many of the products nowadays to tackle usability issues first, as those tend to influence the overall appearance and feel of the design. Finally, they argue that usability can also be solved through form giving and aesthetics. Hallnäs et al. state that "Form is the way material builds things; to build a thing, we form materials." (2002, P.157), with regards to the distinction between form and function, as computational technology is seen as a design material. Additionally, the authors developed an integration between textile materials and computational composites, but without the perspective of producing another "smart" object. The aim was to bring the specific dynamic characteristics of textiles and to pair them with the equally dynamic available technological devices (Kwon et al., 2014). Wiberg corroborates this approach by stating that "the same sensibility for material form and material properties has been applied for the purpose of generating new ideas for design, for inspiring new form-giving activities and for the creation of new objects" (P. 627, 2014). Dourish expresses a different concern, as "there do not exist structured approaches for designers and engineers how to use material properties and cultural material knowledge to construct meaningful, intuitive, and appropriate tangible user interfaces." (P. 625, 2001). The author not only addresses the challenges that come with prototyping interaction design devices but is mostly concerned with the multidisciplinary aspects of materials related to interaction design. Through this thought process, it is believed that materials in this field of practice are not only physical vessels to give shape and aesthetic to devices but can also influence expressions and behaviors through their cultural and contextual characteristics. This multifaceted approach to material-centered design can be driven through physical experimentation, as an active manipulation can also improve the overall understanding of how each material can incorporate a composition (Wiberg, 2013). This also brings a conceptual alternative to interaction design development processes, as it tends to be based on applications and purpose of the available materials, but instead, by focusing firstly on the properties of the materials, their primary features will become emphasized through experimentation, leading ultimately to a design purpose. Even from an artistic and practice-oriented point of view, there are inputs that come from the material manipulation that aid research in theoretical and conceptual methodologies (Nimkulrat, 2009). More on this, Fernaeus & Sundström (2012) express the difficulty of remaking a design artifact on a prototyping phase, it is crucial that the understanding of a material's properties is made in the initial steps of the development process. With this in mind, interaction design can use materials to give structure to the devices even before having a purposeful application. This approach brings HCI research closer to other disciplines that have been focusing on materials and their characteristics, some of which have already been exemplified above, such as industrial design, engineering and textile art, proving that interaction design can benefit from a shared multidisciplinary theoretical contribution. More on this, Lundgren et al., (2006) specify the distinction between industrial design and interaction design as the latter is concerned primarily in defining behavior and its expression while still maintaining an extensive understanding of the design materials. Additionally, although the authors express the qualities and the importance of computational materials in interaction design, it is inferred that traditional materials are the ones to give form to the devices.

C. Compositional material interaction design

Design can be seen as a combination of elements: "parts, materials, functions, structures, processes, activities, and events" (Nelson & Stolterman, 2012, P. 159), and interaction design is no different. Therefore, Wiberg (2018), argues that "even though interaction design is about the design of interaction" (P. 109) corroborated by Rosinski & Squire (2009), it cannot be deprived of understanding the remaining aspects that create the composition in which the interaction will unfold, mainly the materials that give form to it. It is also illustrated that arts, music and even dance (Schiphorst et al., 1990) have been fields that rely on the production of a thoughtful and planned composition to execute the desired results and artistic expressions. Recently, processes of composition are being introduced in the interaction design field, on one hand, for aesthetic necessities (Bauerly & Liu, 2006; Bauerly & Liu, 2008; Bo et al., 2018), and on the other, related to software development and engineering (Alencar et al., 1999; Jing Dong et al., 2000; Keller & Schauer, 1998). Despite yielding interesting results in those approaches, the purpose of looking at composition in this research is to better combine the materials in order to produce a complete process in the interaction design development, that looks into the various aspects of dealing with a varied scope of design materials (Nelson & Stolterman, 2012). Both Wiberg (2018) and Nelson & Stolterman (2012) argue that building a composition with a solid foundation is crucial in the success of a design process since it is impossible to perfectly predict user behavior when in contact with a device, so the designer needs to make sure that the whole composition does not budge when that unpredictable situation might occur (Dourish, 2001). An iterative development is also crucial for a compositional interaction design process. As Wiberg states: "When composing an interaction, the interaction designer needs to move dialectically between these elements and back and forth between the materials, the parts, and the whole in order to bring the composition together." (2018, P. 114). Iteration is not uncommon in the scope of interface design, as Sharp et al. (2019) introduced it as a very frequent topic when discussing interaction design practice. Therefore, the methodology for compositional material interaction design cannot ignore that staple, focusing on a linear process would be contradictory to the research output on the matter (Nelson & Stolterman, 2012). In order to produce a balanced interaction design composition based on a material-centered approach, there needs to be a categorization of the elements that compose it. In a material relation with interaction design there are three elements that stand out in relevancy: the visual, the temporal, and the functional elements of interaction design" (Wiberg, 2018, P. 113). This categorization allows for designers to have a sense of characteristics for the material manifestations of the desired interaction (Dourish, 2001). Wiberg (2014) composed a process that makes for a semi-structured approach to producing an interaction design composition focused on materials, through the categorization of four main components: materials, details, textures, wholeness. Additionally, the author (Wiberg, 2018) goes on to enhance the compositional material interaction design methodology, focused on the practical and "doing" aspects of material interaction. Although it its argued that there should not be a defined and strict procedure to producing design, Stolterman & Wiberg (2020) illustrate general steps to achieving compositional interaction design. Based on the two complementary processes (Wiberg, 2018 and Stolterman & Wiberg, 2020), we recognized an opportunity to illustrate a conceptual methodology for structuring compositional design, focused on material interaction. As Wiberg (2018) argues, the first step for achieving this, is the understanding of the available materials, their characteristics and properties, followed by the selection of said materials for the following phases of production. Then, the focus is on the interactions that can be produced from that initial selection, meaning that the form of interaction is dependent on the capabilities and limitations of the materials, addressed by Wiberg as "activities of material integration, composing and craft" (2018, P. 119). Finally, the process is concluded with the definition of manifestations, as the systems and devices are being finalized through discussion and reflection, allowing for an exploration of the improvements to be made in the composition. To better illustrate this process based on Wiberg's

(2018) thoughts, Figure 14 was produced in order to exemplify the steps of the development in Compositional Material Interaction Design.

Materials
Plastic, Wood, Metal,
Computational Materials, Water...

↓

Desired Interactions
Dynamic Printed Media, Ubiquitous Computing,
Personalized Learning...

↓

Manifestations
Tangible Workbenches, Augmented Reality,
Shape-changing interfaces...

Fig. 14 – Compositional Material Interaction Design.

End Note

As this chapter sought to provide context in interaction design research, through the waves of HCI categorization, the resulting cognitive map allowed for a broader perspective on the present state of the field. With the goal of expanding the research made in this context, this chapter is related to the past, present, but mostly the future of interaction design, as it will, inevitably, be subject to changes in the coming years and decades. Additionally, the interaction-centered design can also foster a concern in which researchers and designers alike can focus on when producing outputs related with the IoT and Ubiquitous Computing concepts.

With this in mind, the materiality of interaction provides a groundwork for an approach that can take into advantage the multimodality of interaction, as aforementioned, as the focus on the materials is versatile both in its theoretical process and its practical development. Wiberg (2018) provided material-centered research that allowed for an in-depth understanding of how its composing concepts can be manifested in the form of interfaces. Not only that, the proposition of creating interaction through the material manipulation can prove to be insightful when looking into the tangible interaction context.

Although the focus of this thesis is the integration of interactive print media with autonomous systems, the desired manifestations of the proposals are based primarily around a tangible interaction approach. The following chapter seeks to provide an outlook for the context, mainly through its conceptual frameworking over the years.

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Chapter 2. Frameworking Tangible Interaction

Ishii and Ullmer (1997) introduced the concept of “Tangible Bits” in which the goal was to “bridge the gaps between both cyberspace and the physical environment” (P. 234), as they recognized that interactions were mostly produced in Graphical User Interfaces (GUIs). This discrepancy of manifestations has remained until nowadays, although there has been a surgency of research that focuses solely on TUIs and its tendencies for the future. Fishkin (2004) produced a taxonomy on the “unmarked trends for TUIs”: Children’s storytelling, Tangible workbenches and Control widgets on an augmented desktop. Even though those tendencies were confirmed within the output of the scientific community (Raffle et al., 2004; Antle, 2007; Mazalek et al., 2002), the scope has also expanded with the advancements of both HCI research and technological innovation. TUI research has also been connected with concepts such as Shape-changing Interfaces (Nakagaki et al., 2016) and IoT (Angelini et al., 2018). Alongside a practical approach to TUIs, there has also been a focus on producing “guidelines, models and taxonomies” (Mazalek & van den Hoven, 2009, P.226) in order to inform interaction designers as to the concepts, processes and results used in this field of research. Although Mazalek and van den Hoven (2009) shared an in depth categorization of frameworks regarding tangible interaction, considerable time has passed. This means that a reassessment of the updated research on this topic might prove useful in order to promote a more concise line of thought when it comes to establish a framework for tangible interaction.

1. Existing lines of thought

A. Tangible interaction research tendencies

As Mazalek and van den Hoven (2009) state, “more tangible interaction frameworks should be based on approaches other than software engineering, for example, based on fields that have a long history of interaction with the physical world” (P.234), alluding to the lack of HCI research, particularly on

TUIs, from fields such as “product design, arts, psychology and embodied cognition” (P.234). This thought is shared by Ullmer and Ishii (2000) as the authors infer that “relatively few tangible interfaces have been strongly shaped by industrial design and other traditional design perspectives” (P.8). This is a tendency that was specific to TUIs, as designers have had a considerably bigger impact on GUIs, therefore recognizing the discrepancy between the two interfaces and their related research. From this point of view, van den Hoven et al. (2007) call for an integration of knowledge between various fields of practice, with the goal of promoting research from a product design standpoint. The authors also compare production design’s broader span of contexts-of-use, as HCI practice is intrinsically connected to a work environment. Both fields are also distinct in the approach for physicality, as TUIs were proposed initially to mainly manipulate digital information through physical artifacts (Ullmer, 2002), while product design is “concerned with physicalizing interaction while expressing functionality.” (van den Hoven et al., 2007, P.110). With the increase of research on interaction design, tangible interface studies were simultaneous with the definitions of concepts such as IoT (Angelini et al., 2018), Ubiquitous Computing and AR, not only producing more opportunities for physical manipulation, but that tendency would also change the inherent concepts of TUI design (Do & Gross, 2009). With this in mind, the evolution of tangible interface research is very coherent with these advancements. Firstly, Ishii and Ullmer (1997) contextualized the tangible bits concept in a considerably juvenile HCI research. At the time, GUIs were desktop based, the input of information on a device was made mainly through physical bodies, particularly with the computer mouse and keyboard, which then transferred the information into a computational system and afterwards displayed the information in a display monitor (Ullmer & Ishii, 2000). The concept that followed was to produce interfaces in which the final phase of interaction was physically represented, not through a digital medium, therefore replacing the representation-driven interface with a physically embodied one. Most first-generation TUIs were mainly characterized by that, as digital compositions that were added a tridimensional enhancement that would add physicality to a digital media system (Ullmer, 2002). This also prompted the introduction of AR, as physical bodies could be used as markers to create digitally augmented devices is a tendency that started in this phase of both HCI and TUI research (Billinghurst et al., 2001; 2008). In the following generation, tangible interaction researchers acknowledged the potential for interfaces that were dynamically manipulated, not only mirroring the capabilities of a digital system, but also changing its physical properties according to computational information (Ishii, 2008a; Nakagaki et al., 2016). This introduced the concept of 'shape-changing interfaces', as engineers and designers experimented with the properties of materials when subject to certain actions and the results were not necessarily very high-tech, although there are examples of both levels of complexity and technology (Coelho & Zigelbaum, 2011; Rasmussen et al., 2012). Since then, Ishii et al. (2012) have developed those ideas into what they called "Radical Atoms" as they believe that should be the future for tangibility in interaction, the merge between physical and digital information. Although Ishii only published his ideal of Radical Atoms, Gorbet (1998) already tried to push the fuse between digital and physical aspects of tangible interaction as he states: "Bits or Atoms? Both." (p. 7). This brings us to reflect that there is no specific formulae to produce tangible interfaces, as there are so many possibilities in the scope of materials, technologies and contexts. Therefore, defining tangibility is a challenge, and as Fishkin (2004) argues, tangibility is "a spectrum rather than a binary quantity" (P. 357), and Wiberg (2018) adds that even immaterial interfaces are required to have a tangible characteristic.

B. Expanding beyond tangibility

When Ishii and Ullmer (1997) introduced TUIs, in complement of the more-known GUIs, the output for those was mainly supported by desktop computers, as smartphones were not yet part of the interaction design approach, as they are now. Additionally, one of the examples for TUIs used by the authors was the Marble Answering Machine, by Durrell Bishop, which illustrates the evolution that phones had in the following years (Fig.15).

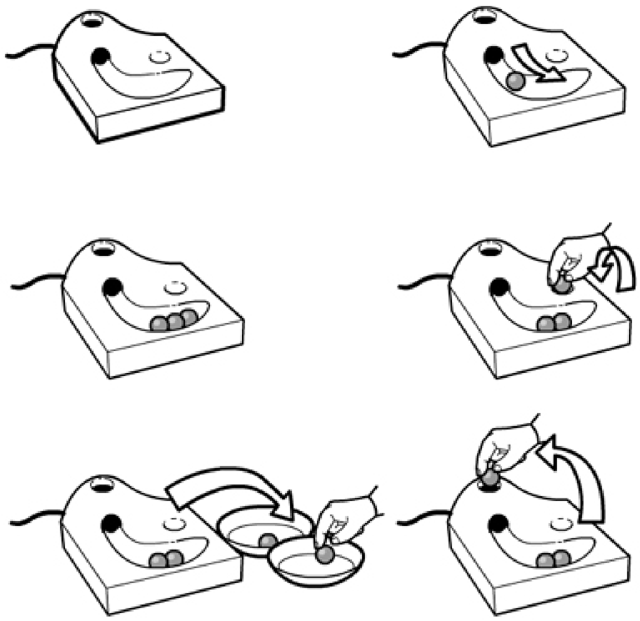

Fig. 15 – The Marble Answering Machine by Durrell Bishop. Source: Jones, M. (2013)

Although there might be distinctions between TUIs and GUIs in their physical properties, both can be considered to have tangibility, as neither are invisible and immaterial, there is always a physical aspect to both, even if it is just through its manifestations of media (Fishkin, 2004). With the evolution of TUI research, Hornecker (2011) considers that physicality is the distinctive characteristic in this context, as tangible interfaces can exist through digital manifestations. Tangibility is therefore a broader approach to interaction design, with physicality being a more specific quality that relates more to the embodiment of interaction, that Hornecker designates as "Expressive-

Movement-centered view" (2011, P.1), albeit still present in other contexts of tangible interaction. Embodiment of interaction is not a new concept to the field of HCI (Dourish, 2001), as it has closely followed the evolution of tangible interaction research (Jensen et al., 2005), and has inclusively influenced the previous chapters that focused on the materiality of interaction (Wiberg, 2018). In this topic, materiality emerges in the 3rd wave of HCI context with the objective of contrasting with the increasingly immaterial interfaces. Bakker et al. (2012), had the same goal and their approach was mainly "people-centered, iterative approach to the design of interactive learning systems with embodied metaphor-based mappings" (P. 434). As embodied metaphors are a tool that allows for an additional dimension to be seen and explored, it has been naturally applied to learning contexts, especially with children (Antle, 2007; Liang et al., 2021). Although the embodiment of interaction has become a research tendency lately, the introduction of concepts such as materiality and physicality can prove to be stimulating tools to accomplish a goal in common. As Robles and Wiberg (2010) have discussed, the material turn can promote an approach that understands materials in full, allowing for an improved method of the embodiment of interaction. As materials tend to be of physical, solid nature, it is appropriate to see material-centered design as a tool to achieve embodied interaction design (Hornecker, 2011), especially when applied to representation-driven interfaces. Additionally, when reviewing the methodology of compositional material interaction design (Fig. 14), the embodiment of interaction can become crucial to the whole process, as it can easily be included in the Material/Interaction/Manifestation iterative development. Robertson (1997) describes a "taxonomy of embodied actions", in which he categorizes user behaviors in relation to an interface and in relation to other users. Although this list of "embodied actions" had a theoretical and abstract weight to the research, it recognized a series of opportunities that in this materiality context can be transferred exactly into the "desired interactions" section of this methodology. With this in mind, there needs to be a conversion from an abstract idea into concrete physical actions, and those need to be as explored as dynamic movements in typical GUI interfaces (Jensen et al., 2005). As Dourish (2001) believes, interaction design does not have a specific model to create interfaces by, be it through digital GUIs or by embodied metaphors, there is a belief that HCI research and practice will evolve systematically.

2. Physicality of Interaction

A. Revisiting physical-oriented frameworks

Due to the nature of the research, with a material-centered approach, focusing mainly on physical-oriented frameworks meant that the assessment of already existing frameworks would be more enlightened by the literature review, as well as having the opportunity to create a tangible interaction framework that could incorporate a material-based point of view. It is also important to note that in the map produced by Mazalek and van den Hoven (2009), there is a field dedicated to interaction-focused frameworks that could be complemented with a third wave of HCI thought process, but that is not the goal for this chapter, as the frameworks focused on a physical practice are the most related to a material-centered interaction design approach. Figure 16 represents the selection of the specific section that is going to be thought-off in this research.

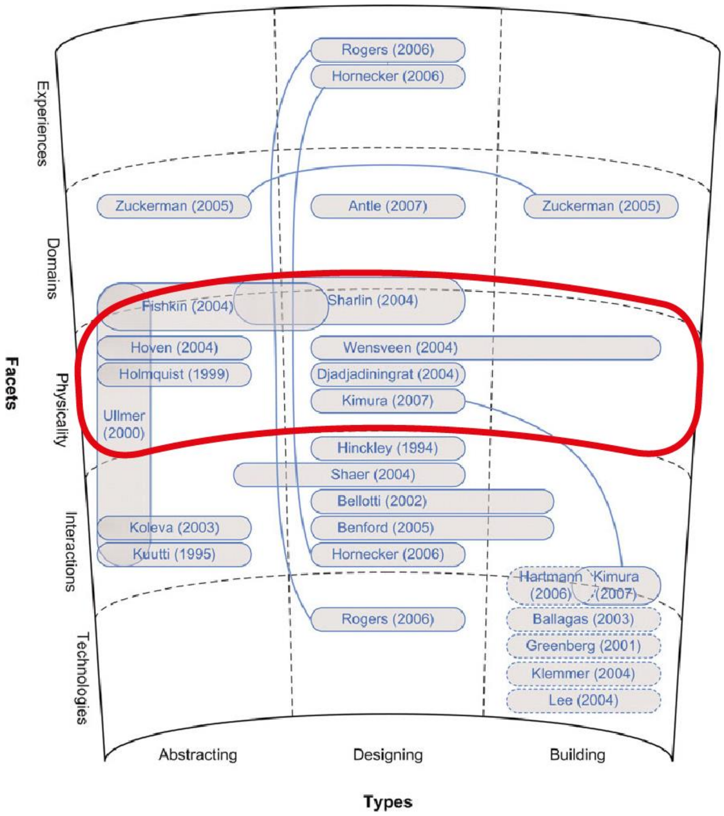

Fig. 16 – Map of Tangible Interaction frameworks. Adapted from Mazalek and van den Hoven (2009)

Considering that the original map (Mazalek and van den Hoven, 2009) was published in 2009, it might be expected that there would be an increase in the quantity of physical-oriented frameworks in the following years. Although the number of publications on tangible interaction have increased since then, there is still a challenge in acknowledging research publications that attempt to complement or refute the above considered frameworks. As said by Mazalek and van den Hoven: "Some papers talk about frameworks, others about guidelines, models, or taxonomies. Although these terms are often used interchangeably, there are subtle and important distinctions." (2009, P. 226). This was difficult, as the term 'framework' was used frequently on tangible interaction publications, both as a way to delineate specific processes for projects or contexts, such as privacy-oriented guidelines (Mehta et al., 2021) or a tangible software production framework (Krzywinski et al., 2009); as well as to give reference to the already established frameworks that the research would be based on. This meant that the quantity of publications that attempted to characterize or give evidence to certain tendencies of research in tangible interaction were still fairly low. While initially the goal of this section was to have a systematic literature review output on the broader scope of tangible interaction frameworking research, a more fluid approach based on case studies can still provide stimulating insights. A case study of the frameworks was a contemplated method for this phase of research, but as each model has its own set of characteristics and goals for the tangible interaction setting, we believe that they should not be assessed as comparable or in opposition, but as complementary. Additionally, few models were considered to not be in line with the goals of this research as some dealt with very particular contexts and only tackled a specific interaction component, while still being relevant for the evolution of TUI design. Therefore, researches such as Kimura et. al's toolkit for implementing TUIs (2007); the research by Sharlin et. al (2004) that proposes the introduction of specific heuristics in spatial TUIs and Antle and Wise's (2013) classification of elements for tangible-based learning, were not selected to be assessed in this phase.

Holmquist et al. (1999) Token-Based Access

Chronologically one of the first publication to focus on tangible interaction design, more specifically in token-based interaction, Holmquist et al. (1999), provided an in-depth comprehensive vocabulary to categorize components of this type of interaction. The authors believed that the introduction of ubiquitous computing in the interaction field would be inevitable, as "computers would leave the desktop and move into the world that surrounds us" (P. 234). In line with this tendency, Holmquist et al. sought to "propose useful terminology that attempts to identify and generalize the functional building blocks of tangible interfaces" (Ullmer, 2002, P. 63), much like Ishii and

Ullmer's research (1997; 2000; 2001). Not only that, but the concept of adding physicality to the inevitability of immaterial interfaces that Wiberg and Robles (2010) promote, was already a concern for the authors (Holmquist et al., 1999). The token-based approach was in its initial stages at the time but defining two sets of components would allow for researchers to continue and improve the line of thought in which the authors (Holmquist et al., 1999) were focused. The first set is related to the representations of information by physical objects, in which those are divided into containers, tokens and tools. Containers are the main support of the interface, in which the computational materials will be integrated in, and is typically the main digital surface of a tabletop workbench, for example. Tokens are usually movable pieces that are external (Fishkin, 2004) to the container component, and physically represent the information that is being manipulated. Tools' functions are related to altering the state of the digital information while having close proximity to the interface, allowing for change in scale (Fitzmaurice et al., 1995), size, color, volume, depending on the desired interactions. Then, Holmquist et al. (1999) defined the two components for token-based interaction with users: access and association. Access is the main purpose of this approach, as it is made through tokens, and making the information responsive, dynamic and available is at the forefront of these types of systems. Finally, association is the characteristic that relates the nature of the token to that of the context, as users tend to disconnect from the interaction flow if that integration is not properly thought of. Additionally, the authors also mention material selection as an important part of the token-based approach, as materials can dictate the time of interaction, influenced by durability, visual aspect and textures of the interface. Although it is not thought of materiality as a conceptual model to introduce in the development of the interaction (Wiberg, 2018), there is already a concern to explore and understand the properties of said materials.

Fishkin (2004) Taxonomy for and analysis of tangible user interfaces

Following the definitions of Holmquist et. al (1999) relating to token-based access, and Underkoffler and Ishii's (1999) classification of object meanings in the same year, Fishkin (2004) sought to create a taxonomy (Fig. 17) that would classify examples of tangible interfaces and therefore allow for the production of a preview of the future tendencies for TUI research. The author not only provides relevant research in the form of tables to contextualize the tangible interaction research state, but also presents a very thorough analysis on the interaction by itself, in a TUI context. Although Fishkin (2004) produced a very straight-forward graph for the trends of TUI, the description and definition of the levels of metaphors and embodiment are particularly relevant to comprehend the possibilities in which researchers can encounter opportunities to develop their tangible interfaces. Instead of funneling tangible interfaces into specific definitions, the author allows for a freer definition of tangibility, meaning that there is always a context in which interaction can intervene, be it a fully embodied interface, or the most immaterial representation. This point of view can also promote multimodal and multidimensional interfaces, in which different segments of the interaction can have specific manifestations, while still maintaining the compositional values.

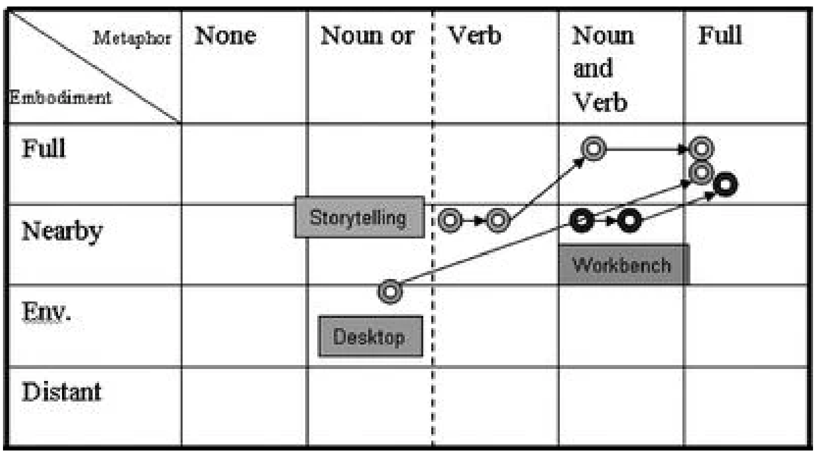

Fig. 17 - The evolution of TUIs. Source: Fishkin, Kenneth P. (2004).

Ullmer & Ishii (2001) MCRpd model

This model from Ullmer and Ishii (2001) sought to acknowledge and compare the interaction interfaces between representation-driven, typically related to digital systems; and physically represented information, usually in the form of TUIs (Fig. 18). This framework represented the connections between modules that compose interaction and from the typical GUI model evolved into an interface that would allow for physical manipulation of digital information. The main difference was not only the introduction of a new format of manifestation, but the removal of the separation between input and output in the MVC model. This is in line with Ishii's related work (1997) as he believed that the complementary natures of bits and atoms would make for more complex and interesting interfaces. This would permit for multimodal and dynamic experiences between user and interface, guaranteeing that an interaction could follow a back-and-forth relation (Norman, 1988). Although this model does not seek to explain how physicality can be expressed from a practical standpoint by creating a strict series of steps to follow, it is a simple representation in which researchers can build upon. This framework not only presented a proposition for input and output relations, but it also expressed that the graspable physical control for input can also be the main surface for information. While at that time, it was not yet pronounced as such, but this can also be seen as a possibility to include haptic feedback on the control and physically represented digital information module of interaction. The original MCRpd model (Fig. 18) is later complemented by another iteration of the framework by the same author (Fig. 19).

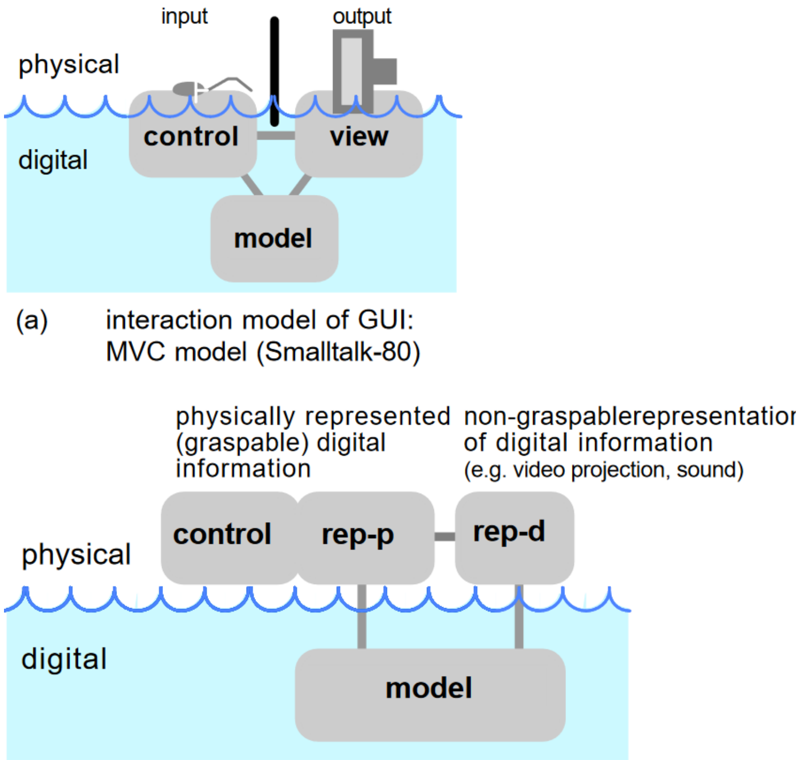

Fig. 18 – MVC and MCRpd models. Source: Ullmer, B., & Ishii, H. (2001).

Although there is not a significant difference in the overall structure of the model, the main takeaway is the visual representation of the framework. While the first opted for a simpler and geometric approach, the added representation and distinction of the modules as well as the additional arrows for understanding the relation between the parts allows for a better visualization of the process. The differences in height for the sections of the TUI, and its relation to the physical/digital space allows for a specific localization in the physicality scope. This can also be integrated with a materiality perspective, as materials can change the outcome of each of the system's devices depending on the material properties that will be manipulated. The representation of opacity in the input module, in contrast with the transparency of the output can present designers and researchers with a possible norm for differentiating the two. Although this model takes into account a tangible output through the same vehicle of input, there is an added intangible feedback that can complement the experience through the dynamic nature of digital information. This framework was the representation to what Ishii (2008b) and Ullmer and Ishii (2001) acknowledged as tangible bits, but this train of thought has evolved into the concept of Radical Atoms (Ishii et al., 2012).

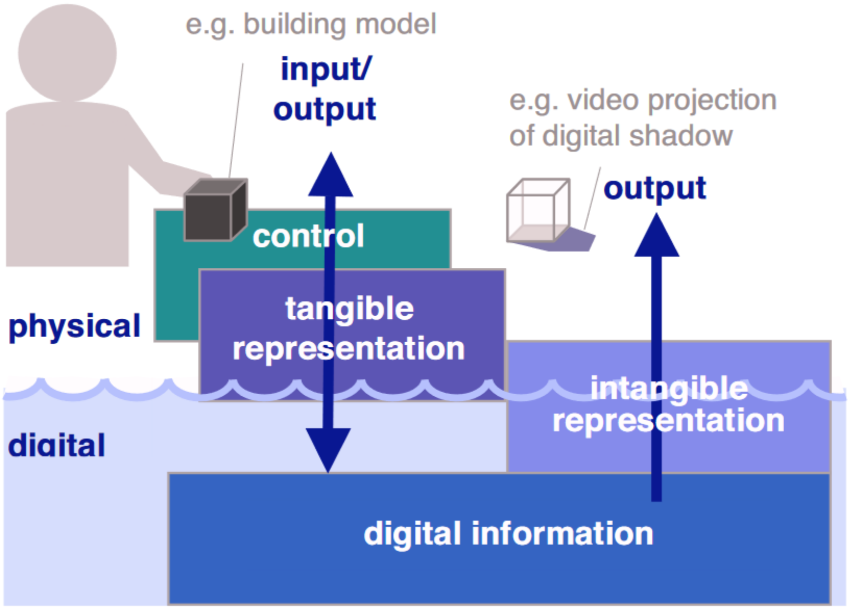

Fig. 19 – Second iteration of the MCRpd model. Source: Ishii, H. (2008b).

Ishii et al. (2012) Radical Atoms

Considered by Ishii et. al the epitome of tangible interaction, "in which all digital information has physical manifestation so that we can interact directly with it" (2012, P.40), Radical Atoms no longer tries to bridge tangible and digital devices, but seeks to integrate them into a unified state. The model (Fig. 20) represents the interaction flow and the cause-effect relations between each stage and the state of the interface. It offers a more complex and deep understanding of how the Radical Atoms concept can come into fruition both in a theoretical train of thought, and through the transformations of the different aspects of the interaction. The model can be divided into three different input devices that affect the single or multimodal output, be it through physical materiality, by a digital representation of it, or the complementary natures of both. Before the interaction starts, the constraints need to be taken into account, be it from the user's perspective or from the interface's properties. Firstly, the user instructs the physical control device with the input manipulation, transforming it into another material state. Simultaneously, a digital response is following the input to later update the output material that is going to inform the user through both channels of interaction. In complement to the previous models, the Radical Atoms framework introduces an extra component to the tangible interaction flow, materiality. When Ishii et al. (2012) mention "Material can transform by itself to reflect and display changes in the underlying digital model" (P.46), the authors are in sync with material interaction design perspective from Wiberg (2018). This is another argument to promote the tendency of introducing a material-centered process in tangible interaction design. While Wiberg & Robles (2010) found that the increasingly immaterial expressions of Ubiquitous Computing and IoT interfaces as an opportunity to introduce material properties as a complement; Ishii et. al (2012) identified materials as the next step to enhance tangible interaction with dynamic physical manipulation.

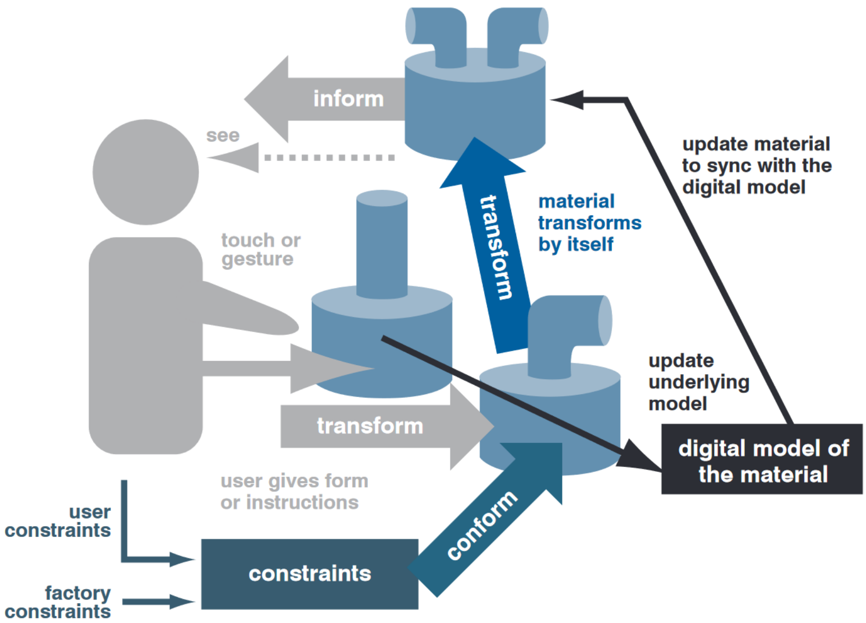

Fig. 20 – Radical Atoms interaction model. Source: Ishii, H., Lakatos, D., Bonanni, L., & Labrune, J.-B. (2012).

Wensveen (2004) The Interaction Frogger Framework

Considered by Mazalek and van den Hoven (2009) as a model that not only can be related to a designing aspect of tangible interaction but is also identified as a system that can enhance the building process of TUIs. While previous research was focused on the manifestation and structure of TUIs, with the goal of classification and categorization of certain aspects of embodied interaction; the model by Wensveen (2004) is concerned with the "coupling of action and function" (Fig. 21). The author produces a categorization and definition of natural coupling, feedback and feedforward. Natural coupling is divided into six aspects that characterize interaction and "unifying action and reaction on each of these aspects makes the interaction intuitive" (Wensveen, 2004, P. 3). Feedback is a known concept of interaction design and the author defines three possible manifestations for it: functional feedback, which is the main stream of connection between user action and direct reaction from the interface; augmented feedback that is not inherent to the action, but serves as an addition to user action, prompting the device to include more information; and finally, inherent feedback is specific to the physicality of the artifact, as sound, touch and feel are aspects that influence user's action. Additionally, Wensveen (2004) also touches on the concept of feedforward, in which the device offers orientation to the user, before the action takes place. Manifestations of feedforward are similar to the categories of feedback mentioned previously. The framework serves as an expression of the coupling of user action and device's feedback and feedforward, as it presents possibilities in which interaction could take place, taking into account the types of feedback that are desired. Anastasiou and Ras (2017) also address this, complementing Wensveen's (2004) research on different modalities that can be used to provide feedback and feedforward in a TUI context.

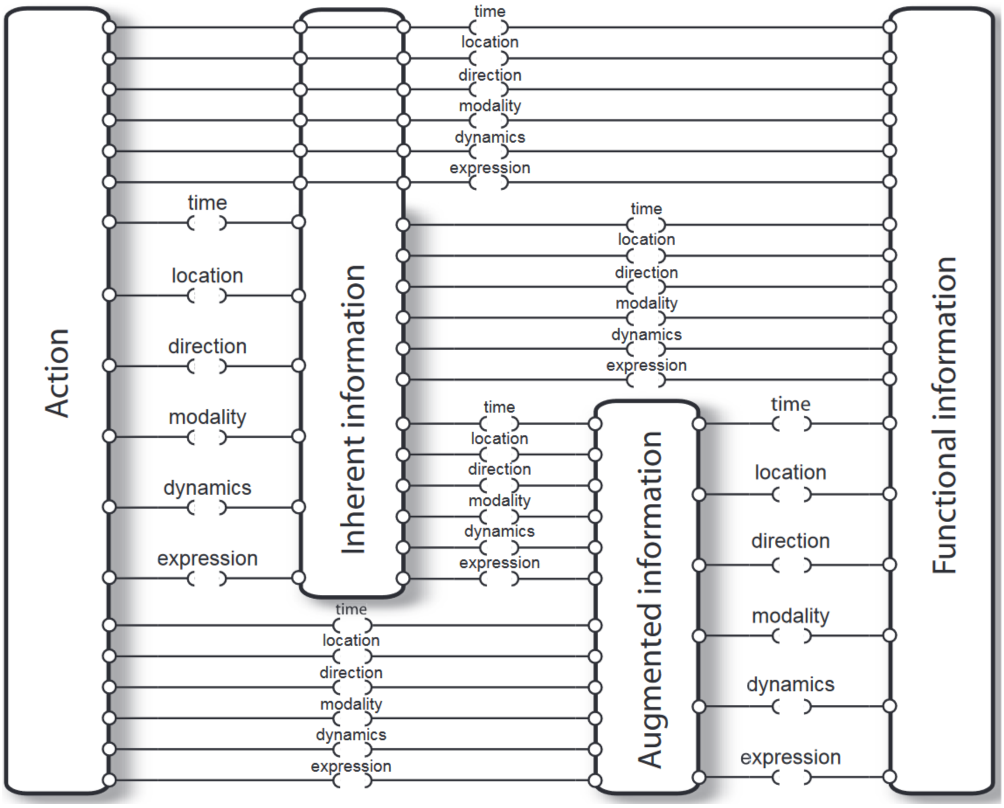

Fig. 21 – The Interaction Frogger Framework. Source: Wensveen, S. A. G., Djajadiningrat, J. P., & Overbeeke, C. J. (2004).

Nishino et. al (2010) Framework for haptic devices from multiple applications

In line with the focus on the building aspect of TUIs, Nishino et. al's (2010) research had similar concerns, mainly in the manifestation of feedback in haptic devices (Fig. 22). The authors express the main features of haptic displays and how they can complement GUI design, through a tangible reactive technology. While the publication focuses on implementation of haptic technology on digital systems, the proposed framework can still complement previous models, as it expresses both the possibility of multimodal interfaces, and the categorization of different types of feedback. While the model authored by Wensveen (2004) has a more thorough delineation of the configuration of feedback, distinction of tactile and force feedback devices can still be included in the previously mentioned Interaction

Frogger Framework (Fig. 21). Even though Nishino et. al mention 3D Haptic Applications as specific to GUIs, the point can be made that those access points can also be seen as the control devices that Ishii and his colleagues (2008a, 2012) have considered the first piece in the tangible interaction composition. This can allow for physical input devices to be augmented by haptic technology, promoting a more dynamic and responsive system. The haptic devices framework also takes into account the need for the design of tools that integrate digital and physical components, promoting a seamless hybrid composition. Nishino et. al are also concerned with physical constraints of each module of interaction, as the group takes careful attention to computational materials that integrate haptic devices.

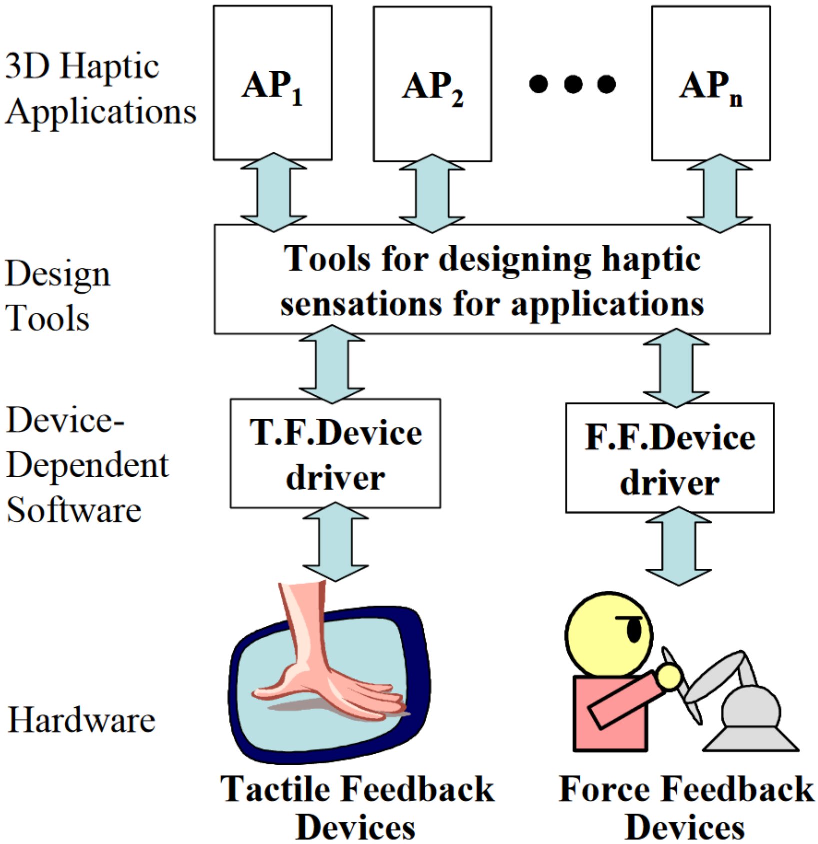

Fig. 22 – Architectural framework for sharing and reusing different types of haptic devices from multiple applications. Source: Nishino, H., Goto, R., Kagawa, T., & Utsumiya, K. (2010).

Giaccardi & Karana (2015) The materials experience framework

Although not necessarily a tangible interaction framework, the model by Giaccardi and Karana (2015) can function as a bridge to the materiality that has been focused on previous chapters. Although the framework (Fig. 23) does not present a physical manifestation or a series of steps to add understanding to the tangible interaction approach, the nature of the model can enhance that same area of interaction. The "materials" module is related to properties and capabilities of the interaction artifact, while the authors "make no distinction between physical and digital materials." (Giaccardi & Karana, 2015, P. 5). The "practices" segment consists of the interaction possibilities in which the interface can manifest itself, while the "people" section is the expected recipient of the interaction, as interaction and feedback are centered around the user. The triangular relation between the three vertices can prompt inclusion of an additional dimensional, broadening the scope of TUI and material research. As tangible interaction design can be considered a "practice" in the above model, previous frameworks in this chapter deal with the relation between that specific practice and people (Fig. 18, 19, 20, 21 & 22), the addition of a third element, materials, can be element that enhances the tangible interaction experience.

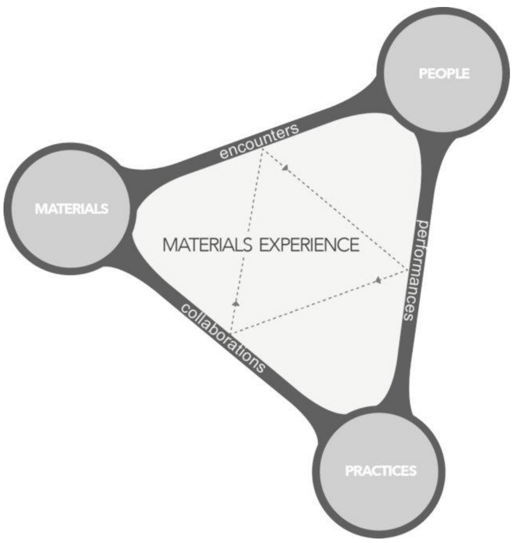

Fig. 23 – The materials experience framework. Source: Giaccardi, E., & Karana, E. (2015).

B. Merging previous frameworks

After the analysis of previous frameworks, we outlooked as to where a new representation would provide insights to a possible tendency for tangible interaction design. The presented schemes attempted to tackle specific concerns in TUI research, as will the produced framework in this section. The main purpose of this phase was to integrate the materiality concept into the User/TUI interaction, as it is believed that there can be an enhancement both conceptually and through its physical manifestation. Additionally, given the complementary natures of previous frameworks, there would also be an attempt to produce a structure that allowed for the integration of the concepts focused by each of them. Not only that, but the proposed congregation is not a final piece of research, as it is planned that there can be adjusted and additions in future publications. Giaccardi and Karana's diagram denotes (Fig. 23) the Materials-People-Practices modules as the main concepts for material experience, and tangible interaction design is mainly an approach related with interaction design Practices. These two relations with material-centered processes and tangible interaction served as the starting point for the production of our proposed framework, using a triangular scheme that merged the components of previous structures.

Firstly, Ishii et al.'s (2012) scheme that defined the Radical Atoms model (Fig. 14) provided an in-depth comprehension of the process that started with user input and ended in the transformation of the interface, providing feedback to the user. On one hand, changes that would occur in the configuration of the interface were clearly defined, the framework lacked a visualization as to how the material would describe the physical constraints and give shape to the interface, other than being a granted property of the interface. This was one of the goals for the proposed framework, as we believe that materiality, if seen as a focal point of the interaction, can help to produce more complex and complete interface experiences. On the other hand, there is a concern in demonstrating how the TUI can transform during the interaction, both on a physical matter and on a digital standpoint. Building on these ideas of updating the physical appearance of the artifact is one of the concepts that justify the integration of materiality in the TUI frameworking scope, as that can occur through exposing materials to certain conditions. Expanding on how this control of material properties might prove to be a challenge, as the array of materials that can be implemented in interaction design is quite extensive, as well as their respective characteristics. Therefore, the proposed framework would focus on the conceptual aspects of integrating materials in TUI design, as its relationship with the user would provide meaning to the interface.

The second aspect that would be focused on the proposed framework would be the relation between user and computer, as previous research has proven insightful as to the multimodality of the possible reactions by the interface. Schemes produced by Wensveen et. al (2004) and Nishino et. al (2010), in Figures 21 and 22, respectively, sought to tackle this specific component of interaction. As both structures represent the two-way arrow configuration to express the give and take nature of interaction, there is a concern to demonstrate the possible variations of feedback. As the Interaction Frogger Framework (Fig. 21) denotes, there are various channels that can be used to provide not only feedback but also feedforward in the TUI scope. This complements and deepens Ishii et al.'s (2012) understanding of how the interface can produce a specific response to the user, as they denote specific manifestations of how that can be expressed. We argue that each of those possibilities lie in the characteristics of the materiality of TUI, as inherent information is directly connected to the touch and feel of the artifact; augmented information might be further away from the physical components, but the concept of materiality is based on a composition that has a solidified meaning and the interface would not be deprived of that. Finally, functional information is the most linear relation to the materiality as it is expected that the TUI will react through its physical configuration and provide a concrete response for the progress of the interaction. In addition to this categorization, Nishino et al.'s (2010) framework for feedback through different channels also tackles an approach for a dual channel device configuration, tactile and force feedback devices. These two structures of TUI feedback can help to define the output that the other frameworks overlooked, even though those were focused on other aspects of interaction.

C. The M-TUI model

With the definition of the two main focus points for the proposed framework being the TUI description by Ishii et al. (2012) and the feedback centered schemes by Wensveen et al. (2004) and Nishino et. al (2010), the following step was to find connections between them, while attempting to add a third layer, focused on materiality. We believe that there is an opportunity to include a material dimension on tangible interaction, as it has proven to be a versatile and multimodal approach to interface design. A model (Fig. 24) was produced to express where the framework fits in a User-TUI context, and to express the possibility of including materiality in the framework.

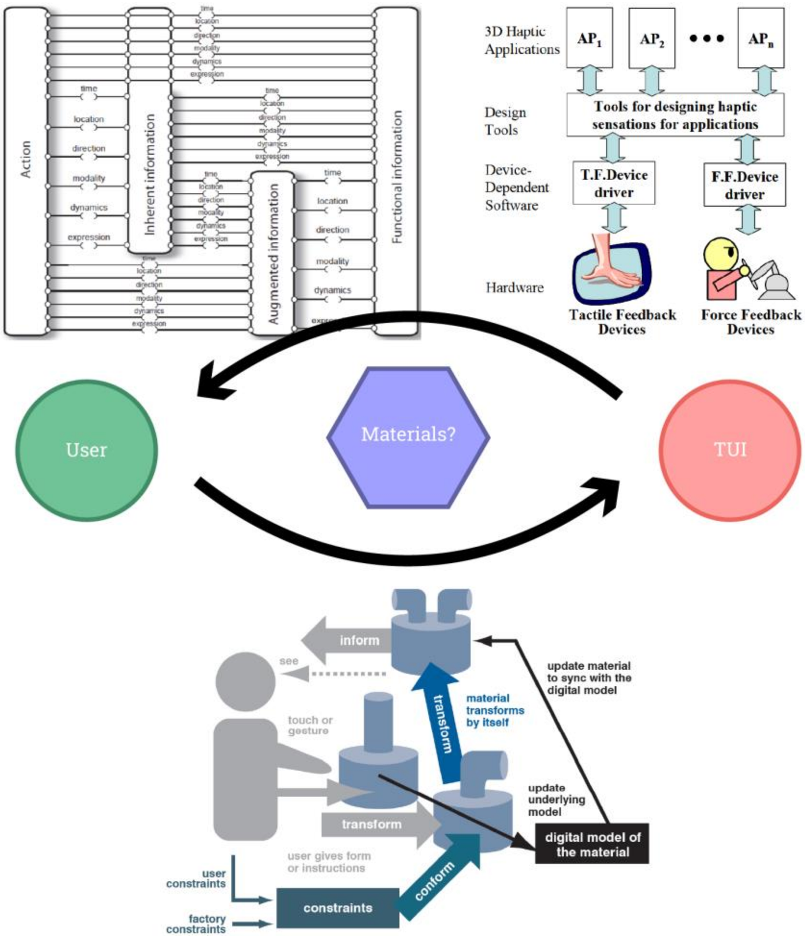

Fig. 24 – Starting model for the production of the proposed TUI framework.

Albeit a very simple schematic, its conception allowed for the structure of the framework to be defined, as it would function around three main focus points, User, TUI, and Materials. Doubts were settled on how the concepts would relate with each other, guaranteeing an interconnection between them. Giaccardi and Karana's (2015) framework provided a very vague definition of those points, describing them as "encounters" for User-Materials and "collaborations" for Practices-Materials. Looking into the materiality definition of the previous chapter, materials provide meaning to interaction, as well as provide a base for touch and feel of the interface, making them relate directly to the User, without having to go through the TUI and its interaction, per se. Collaborations are a simpler connection, as materials provide the physical characteristics of the interface delineating its constraints, shape and form.

Comparison of terms used by researchers was made to better introduce them in the proposed framework (Table 1).

Components \ References	Ishii	Wiberg	Giaccardi & Karana
User	✓	"Desired Interactions"	"People"
TUI	✓	"Manifestations"	"Practices"
Materials	✗	✓	"Materials"

Table 1 – Comparisons between terms used by each researcher to describe concepts.

Not every researcher tackled the three terms being used in this section, but we were able to congregate and mesh each of them in the three original main concepts. Then, the relations between them also needed assessing, as there is also research done in that sense, especially given that those connections were more concrete than the terms discussed in Table 1. While Ishii et al. (2013) and Giaccardi & Karana (2015) were maintained as references in this following phase, Wensveen et al. (2004) and Nishino et al. (2010) would replace Wiberg (2018) as their research dealt specifically with detailed evidence on the multimodality of feedback. This focus on feedback allowed one to better comprehend how the TUI and Materials components would produce output to the user while Ishii's research had already described the possibilities as to how the relations between User and TUI would occur. Finally, Giaccardi and Karana's framework presented conceptual relations that needed to integrate this comparison as it was the first to acknowledge the dynamics between the three terms. Table 2 was produced in order to illustrate this set of comparisons between researchers.

Components	User	TUI	Materials	References
User		Representations Information Performances*	- Haptic/Functional Info. Encounters*	Ishii
TUI	Manipulation/Control Input/Action Performances*		Material Constraints - Collaborations*	Wensveen & Nishino
Materials	User instructs materials - Encounters*	TUI Updates materials - Collaborations*		Giaccardi & Karana

* - Repeated terms as Giaccardi & Karana's framework is based on mutual relations

Table 2 – Comparisons of relations between concepts used by each researcher.

As mutual relations were defined, the following phase would be tahe visual representation of the structure that would comprise the concepts of this chapter. Given that the framework would be set by three components, the initial structure was a triangle that would mutually connect each of the main concepts, as shown in Figure 25.

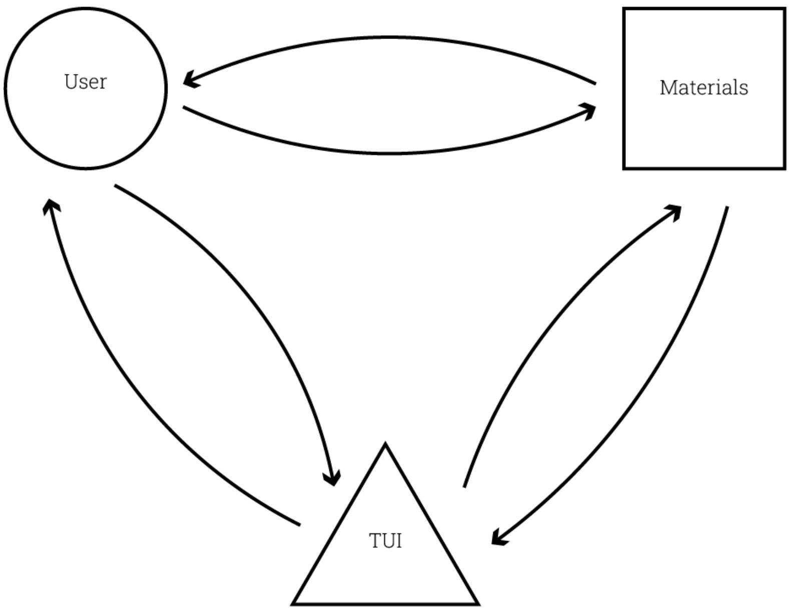

Fig. 25 – First iteration of the proposed framework.

Following this first iteration, relations between each component would be introduced as explored in Table 2, in an attempt to follow the concerns of previously mentioned research. User - TUI relation was clear as the input-output mechanisms as the user would control the device and would expect a representation of the interface. Then, the TUI - Materials connection was considered straightforward, as the properties of the design materials would define the constraints, shape and form of the interface, while the TUI would have the input produced by the User to update the characteristics of the Materials. Finally, the most challenging step was the description of the User - Material relation as the research made in this context is of conceptual and theoretical nature. Nevertheless, as described in the previous material-centered chapter it was expressed that materials would provide the interface with interaction meaning that would appeal to the user through touch and feel aspects. Additionally, as the feedback-focused frameworks described, there are various channels that can be the support for output in this context, and the manifestation of those is dependent on the materials introduced in the interface. To better express the development of this phase, the proposed framework was updated in Figure 26.

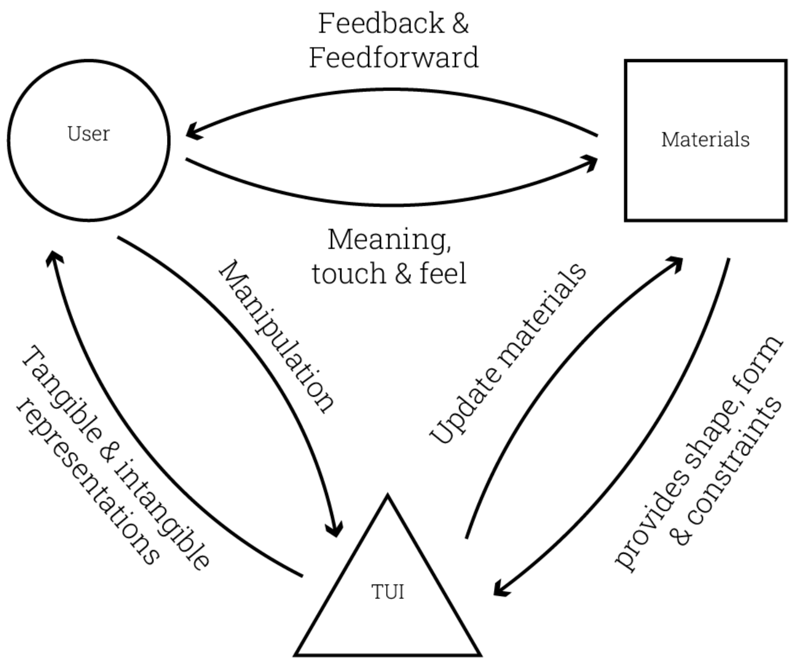

Fig. 26 – Second iteration of the proposed framework.

With the information and structure determined, the following phase was focused on the improvement of visual representation to better express the mutual relations aspect to the model. Therefore, a wireframing process was carried out to create various possibilities of the visual manifestation of the proposed framework. The framework in this step had a sequential nature to the interaction, as each component would influence the next and so on, the maintenance of that relation was crucial in this development process. Not only that, but the visual description of each component both as an individual entity and part of a broader context of interaction was also a focus point. The model would also take into account the conceptual and theoretical characteristics, as well as the physical and representative properties of each item included in the model. The following iterations sought to experiment both with visual hierarchy, the structure and organization of the elements and a clear and intuitive graphic expression (Fig. 27).

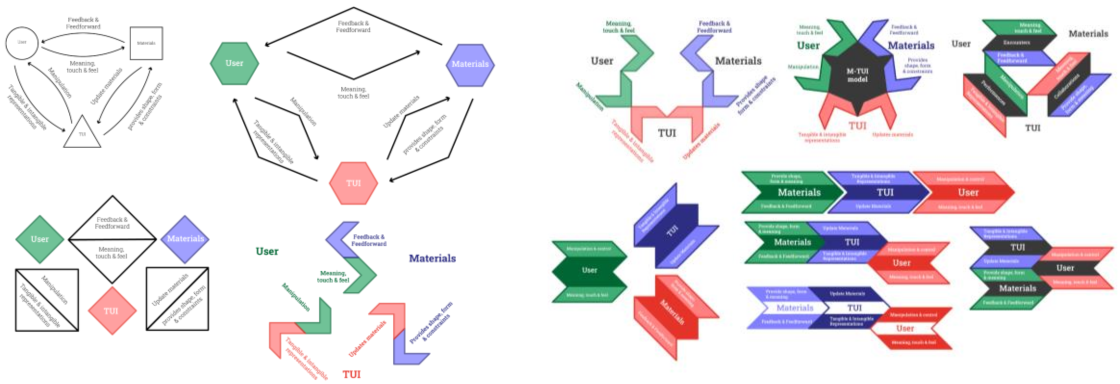

Fig. 27 – Iterations of the proposed framework.

The final iteration of the framework presented a concise approach to the concerns of this chapter and this document, as it covered the aspects that were crucial for the comprehension of a material-centered TUI model (Fig.28). Following an action-reaction process, the shape for the framework had to encompass the sequential nature of the interaction through the Material TUI. Initially, we looked at the User-TUI-Materials as equal and mutually influential to one another, but the main purpose of this chapter was to integrate the material approach into the already established TUI research. Therefore, the Materials are a fundamental element of the TUI, as it is through it that properties and characteristics of said material can be manipulated by the user. With this in mind, the model changed shape and hierarchy to accommodate this thought process, as Materials are inherently part of the TUI, and interact with an outside element, the User.

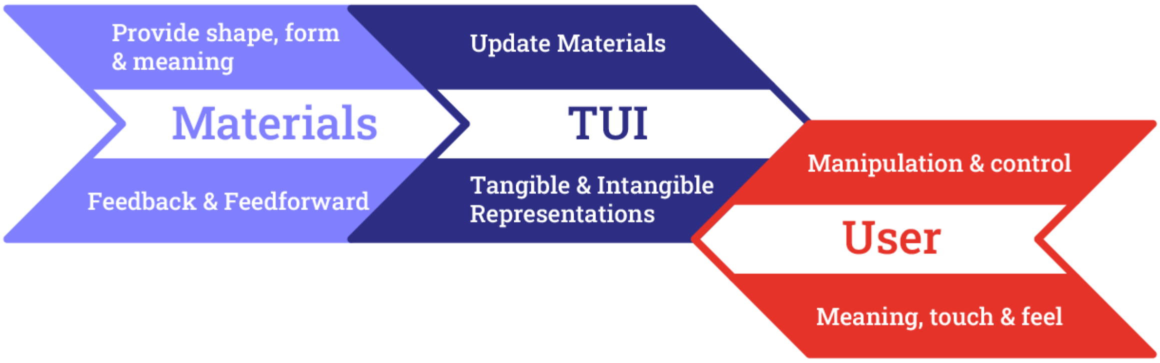

Fig. 28 – M-TUI model.

This is also meaningful as the framework is not a guideline specific to the manipulation or production of a material TUI, but as a general conceptualization as to where each component fits in this context. Additionally, the model also seeks to express how each main concept can influence the two others, promoting a development process that encompasses the nature of interacting with materials through tangible interfaces. The model is named M-TUI as in Material TUI, in line with its inherent concepts and the research goals present in this document.

End Note

The initial assessment of the state of the context in which tangible interaction has been in recent years, as it has expanded in simultaneity with the advances of technology and interaction allowed for a solid groundwork in the development of this chapter. Bridging the starting points of TUI design by Ishii & Ullmer (1997) with tendencies that followed (Fishkin, 2004), gave us a perspective on where there were possibilities of producing a contribution that would address the way of thinking and making TUIs. This came in line with the map that Mazalek and van der Hoven (2009) produced to categorize frameworks regarding tangible interaction. The selection made by the authors (Mazalek and van den Hoven, 2009) allowed us to focus on a single strain of frameworking as it would fit the research goals and the research context. The chosen aspect of tangible interaction for deepening in this chapter was the physicality, inherently connected with the embodied metaphors approach.

Given that relation, the following section focused on how tangibility could be explored in a way that produced a significant enhancement of already existing TUI frameworks. Additionally, we sought to update the assessment made by Mazalek and van der Hoven (2009) as there has been a considerable amount of research made in the years that followed. With this in mind, the following section of the chapter documented the ways in which tangible interaction frameworking has evolved since its first publication. With an overview of the context and tendencies for the structuring of TUI concepts, we developed a proposal in which there could be an enhancement of the tendencies present in previous models.

Tangible interaction has lacked an approach of describing the relations between materials that compose an interface, as well as its connections with the user. This is broadly done by Giaccardi and Karana (2015), as they provide a conceptual and theoretical point of view on how these three components can interact with one another. Given this, one of the main purposes of the framework was to produce a concrete description of the relations between User, TUI and Materials. Following a set of iterations regarding the visual expression of the structure, we devised the M-TUI model, named after the items that compose the framework.

With this chapter, we acquired a deeper understanding of how specific materials can foster new tendencies for the field, regardless of context or approach, given that the proposed framework allows for any type of TUI. As the next step for print media is explored in the following chapter, the possibilities for interaction can be enhanced by the expansive advances that are being made in the AI and ML approaches.

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Chapter 3. Interactive Print and Autonomous Systems

Following the shift to the 2nd wave of HCI, hyperlink gradually replaced traditional print media, as newspapers, books, and other artifacts were digitized and brought into computers and smartphones (Bødker, 2006). Hyperlink media allowed sharing of knowledge to be dynamic, through videos and images, as well as having a much more accessible option. The print industry has had to adapt to this phenomenon, but digital media has not had considerable innovative contributions recently (Barthelemy et al., 2011; O'Sullivan et al., 2017). This is especially significant given the consistency in which interaction design has branched into other opportunities and contexts in recent years (Donovan et al. 2019). Concepts such as AR (Gupta et al., 2020) and Ubiquitous Computing (Weiser, 1991) have been thought of for decades outlining possibilities in which the field can move forward. In this chapter we discuss that it has not been the case for print media. In an attempt to promote the increase of research production in interactive print, we will look into the benefits (Ackerman & Lauterman, 2012) and possibilities (E. Politis, 2019) that are inherent to physical artifacts of traditional print media. Additionally, using print media in a material-centered approach for interaction design, can prompt an alternative way to tackle this lack of production (Dourish & Mazmanian, 2013). That is the goal of this chapter, as we sought to explore contemporary research on the integration of emerging interaction technologies, such as Autonomous Systems, with print media, that lacks attention from the scientific community.

1. Materiality of Print

A. Interactivity in printed matter

In the years that followed the technological expansion that increased the ease-of-access and accessibility of the Internet to the global community, researchers argued that print media would eventually become obsolete, a phenomenon called the "death of print" (Levy, 2012). Although some authors took this concept as a provocation, the purpose of the article was to assess the state of news media in the digital media exponential growth, calling out for a "renewed commitment to journalism and its role in democracy" (Levy, 2012, P. 160). Nevertheless, this prompted researchers to challenge this concept and some tried to provide evidence regarding the comparison of reading in print/digital media (Ghersetti, 2014), while others sought to assess the statistics of each medium for different purposes (Nossek, 2015). With this in mind, the scientific community, albeit on a small scale, hypothesized on what would be the future of print. Tandon (2008), argues that this can be a motivation for "old media to pull up its socks and provide the additional value demanded by a free market where the number of players has multiplied" (P. 1). The author expresses that print media has always been an adaptable practice and support, as it has been through numerous technological revolutions since its initial implementations, and that digitalization is not the end of print media, but its evolution. This thought is particularly relevant to our research, as the goal of this document is that of enhancement of print matter, not its replacement. Therefore, interaction design has become a concept that can explore how static media can move forward, as the print media field finds itself at a crossroads between the old and new. Given the capabilities of digital media, interaction has already become an inherent part of it, as hyperlinking makes for a dynamic and expressive medium in communication (Neves, 2012). As print media was seen mainly as an output of graphic design, the initial concepts of interactivity in this context were of material nature. Exploring how ink and paper would react under certain conditions and movements resulted in Neves arguing that “perhaps we should not consider printed objects as static ones” (2012, P. 34). Interaction design has become its own separate field, although the argument for the complementary natures of both can still be made. Even though static media has been traditionally related to graphic design practice, the point is being made that it can also serve as a material for interaction design (Neves, 2016). Additionally, Neves argues that “the everyday purpose of most printed matter is still to reach its users” (P. 635), which is a characteristic that is crucial to the values of interaction design, bringing the two approaches together. Sarvas et al. (2007), also push for a perspective that tackles the potential of paper, as it is seen as an obsolete and outdated material, named as “dumb paper”. The authors also claim that paper is a material with very specific characteristics and behaviors, and is not dependent on additional devices, as digital media is inherently allocated to its supporting surface. This allows for a much freer manipulation and production of interaction, as “paper can be written on, folded, torn, and so on.” (Sarvas et. al, 2007, P. 4). This is also illustrated by Zhang (2020), as demonstrated in Figure 29.

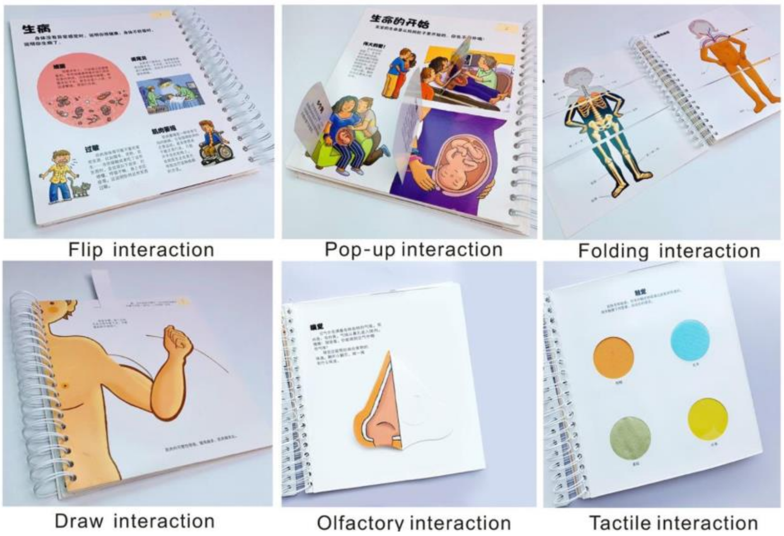

Fig. 29 – Possible interactions with the physical manipulation of paper. Source: Zhang et al. (2020).

Finally, the authors assert that print media can be seen as a type of ubiquitous technological material, as it has become sort of unnoticeable in our everyday lives, through its accessibility and familiarity. Bødker (2006), addresses this question by expressing that “we are still stuck with the idea that new design should replace existing artifacts, rather than exist together with them” (P. 1). This would not mean that researchers should focus mostly on merely analogical print media devices, but the enhancement of said media can promote the conceptualization of interactive possibilities. In a representation-driven context, print media has had a linear transformation to digital media, as it has maintained the basic aspects of graphic design, with recent adjustments given the advances of UX and UI design. This meant that the most noticeable difference of the two was that of manipulation of information. The hyperlink context was initially based on point and click (Moggridge, 2007) manifestation of interaction, but that has since evolved due to the expansion of the field, allowing for dragging, scrolling, swiping and other actions that mimic physical manipulation. In this document, we argue that instead of mimicking interaction with print media, be it through metaphors or embodiment, material manipulation can remain as is with a digital material enhancement.

B. Print media as a material for interaction

Dourish and Mazmanian (2011) focus on the contemporary information society that has mostly dematerialized the medium and supports the sharing of knowledge. The authors believe that even though digital systems have taken over this context, physical manifestations of information will prevail over time given the technological and infrastructural dependencies of those devices. Moreover, they address that media is a material in any given shape or form, as it will always have a physical layer in which it is represented. This is in line with Wiberg’s (2018) thoughts on materials in interaction design, as he argues that even if the manifestation of an artifact is mainly digital, there will mostly always be a material construct that allows for the interaction to happen. As argued previously, paper is a material that offers interactive possibilities, be it by folding or bending, or just for being easily written or drawn on. Although seen as mostly the support for static media, the creativity aspect of manipulating printed matter is stimulating as it is not constrained by the same boundaries as digital media is. Being accessible also allows for a versatility of size, shape, color, weight and opacity, as well as reacting to certain conditions (applying water, heat or wind). If we acknowledge print media as the starting point for interaction, and apply a material-centered process, it is possible to understand that the path for manifestations is not so different from that of interaction design (Fig. 30). Additionally, the nature of print media has been that of following technological advances, and, as mentioned previously (Tandon, 2008; Neves, 2017), it is expected that that remains the norm for this field.

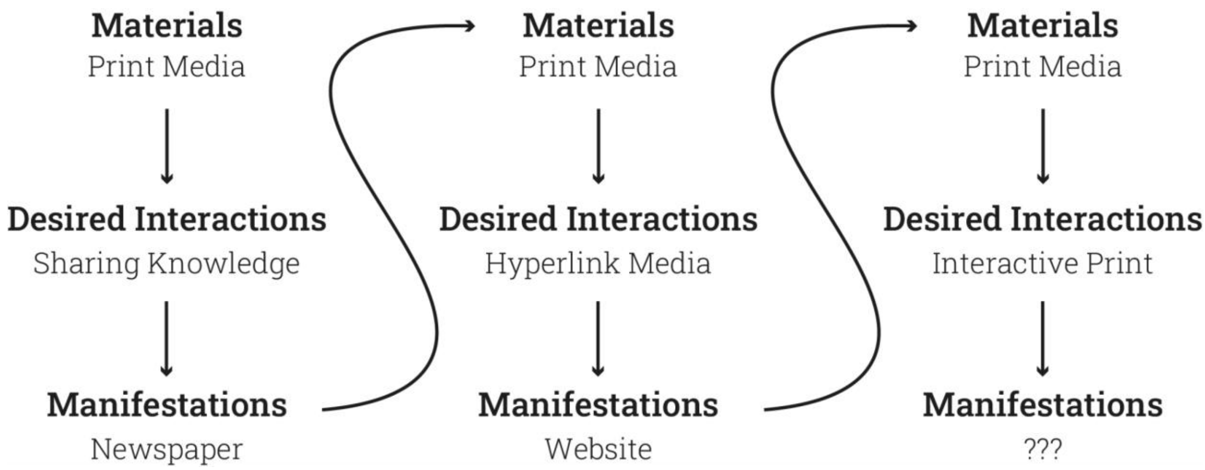

Fig. 30 –Compositional Material Interaction Design in an Interactive Print context.

Neves (2017) provides an outlook for the various designations of print media, as it outlines its versatility of applications, due to the variation in size, shape and purpose. Each of the manifestations for printed matter presents an opportunity for an interactive device, as they can be looked at as a material in itself, not just a variation of print media. On one hand, newspapers, books, magazines, posters have all had a digital counterpoint, and each of those have become much more accessible and have an added interaction, be it by multimedia visuals or by listening to audio. On the other hand, most of the manifestations of those digital media devices have been constricted to the borders of a display screen, be it on mobile devices or on personal computers. One of the characteristics of print media is that of a free manipulation in various methods, and digital media is equally dynamic in its expressive nature, but industry and research has been stale in this transition. Although business cards, packaging and signage are mostly physically manifested mediums of information, characterized by their tri-dimensionality and tangible support, there are emerging tendencies that seek to explore them in an interactive premise. These examples of print media has already been represented digitally, as business cards are now part of profiles on social media, packaging is also making strides in interactivity through RFID and QR Code technologies, while signage has had digital counterpoints in dynamic screen displays. The argument for this document, though, is that when transforming a printed matter into its digital media counterpoint, there is loss of physical manipulation and that hinders the future of the interactive print media tendencies (Zhou et al., 2021). Therefore, we believe that instead of shifting approach from analog to digital, the digitalization can be applied "on top" of the already existing and stimulating variations of print media (Fig. 31).

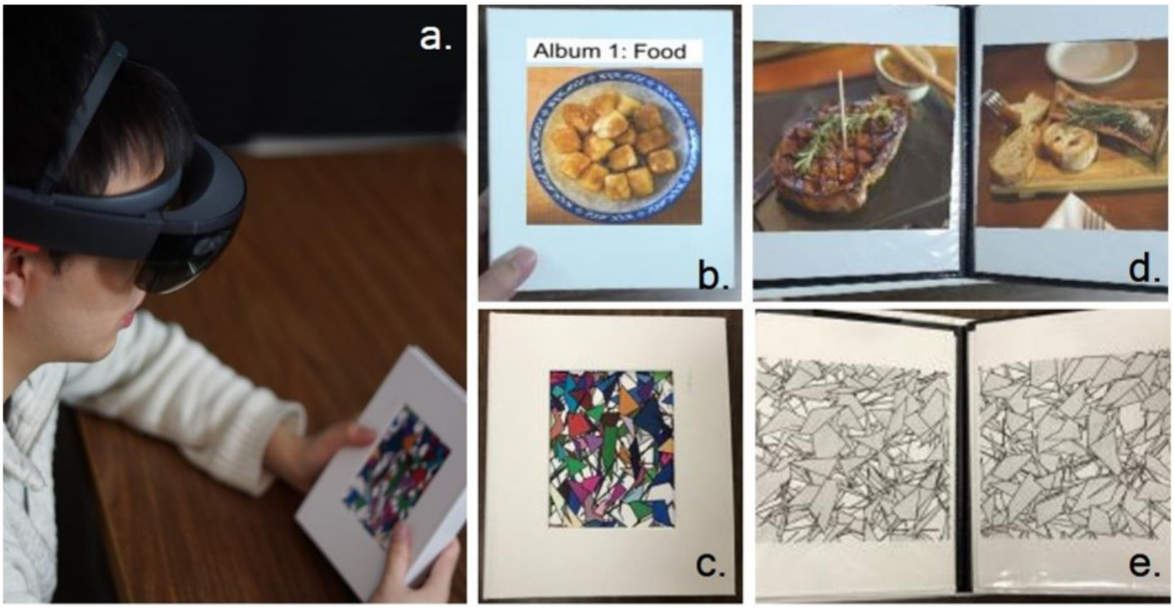

Fig. 31 – Example of an Interaction with a physical album augmented by interaction. Source: Gupta et al. 2020.

This can be achieved through the focus on paper as a material for interaction, already providing support and physical manipulation for possible interactions that can be enhanced by the dynamic nature of digital devices. This integration is also detailed by researchers in the tangible interaction context, as described in the previous chapter of this document. Ishi et al.'s (2012) research regarding Radical Atoms seeks to enhance physical control devices with digital systems, and print media can be an opportunity to achieve that goal. With a versatile material as paper, accomplishing the dynamic and creative manipulation that is characteristic of TUIs can be a stimulating possibility. Tangible interaction research has provided tools for the conceptualization and production of interfaces that do not require high fidelity prototypes to produce insights into the practices related to the field. Additionally, the proposed M-TUI framework (Fig. 28) can be used to achieve such results, as it encompasses the Material concept in a TUI context. This is especially relevant as paper is seen as an accessible tool for wireframing and prototyping both digital (Chen & Zhang, 2015) and tangible interfaces (Coelho & Maes, 2009). This would mean that using print media as a material for interaction can be an element that follows the process of development of possible manifestations in a material-centered approach. Not only that, but the versatility of printed matter can promote introduction of additional materials that enhance interaction. As print media naturally does not possess dynamic interactive properties, the possibilities for the future tendencies of the field can be in the enhancement of this material with computational components that encompass those capabilities. The array of actions that can possibly be done with print media are now on par with the third-wave of HCI practices that can augment the manipulation of an otherwise static material. Combining computational materials with printed matter is a tendency that allows for the integration of autonomous systems to enhance the nature of interaction.

C. Third wave HCI meets static media - new forms of interaction

Although research produced in the interactive print context is fairly recent and has not had considerable quantity of development, there has been an attempt to pair this media with interactive systems. As Donovan et al. (2019) denotes, there is a clear discrepancy of production regarding interactive systems, both 3D and print, in relation to cloud-based services and web/mobile computing. This is consistent with the few research artifacts that were found, usually meaning that if there is lack of scientific contributions, a lack of products of this nature is bound to be a consequence (Nadolny, 2017). Although the research paradigm is fairly vacant, there are still documents that sought to achieve the same goal of this section: enhancing interactive print media systems with AI and ML. As print media is considered a material for interaction design, autonomous systems also provide characteristics and possibilities to greatly enhance the same approach. Luciani et al. (2018) argue with this perspective, as they claim the dynamic attributes of ML systems can greatly improve the actions that influence real-time adaptability of autonomous systems. Although the authors produced research in a pre-programmed algorithmic approach, there were options that delineate possibilities for interaction in this context, mainly through visual and tangible motions. This multimodality of interaction is especially relevant as this can increase the data that the user and the interface provide for the functionality of a ML system. Additionally, this argument is also on par with our perspective on the enhancement of interaction through the complement of print media with a dynamic tangible interaction approach. Moreover, Gupta et al. (2020) produced a series of prototypes that sought to achieve this concept, through physical, AR-augmented devices. The authors also identified that although users enjoy the manipulation with physical print media artifacts, they end up not using them as much as their digital counterpoints, due to the accessibility of these devices, and the possibility of having updatable content. Given this phenomenon, it is clear that integration of dynamic systems in a print media approach can enhance physical manipulation already inherent to traditional media. With this in mind, researchers have started to experiment with possibilities of the pairing of the two concepts, mostly in an educational context, due to the already established use of traditional print media. Nadolny (2017) sought to assess the cognitive load that tasks on an interactive print system would have in two separate cases that consisted essentially of hyperlink multimedia in a tangible support. Although the author was not primarily focused on prototyping visual or interactive aspects, the goal of the research was to prompt other studies that could complement its output. Similarly to Nadolny, Fernandes et al. (2019) developed a mobile marker-less AR application that enhanced static media information with dynamic augmented videos and audio. The researchers also proposed that application of this system could be expanded to other fields, which could prompt innovation and growth of AR-augmented print media devices. Moreover, Lai et al. (2019) had the same goal in mind, as an "AR multimedia textbook" was produced “based on the contiguity principle of multimedia learning” (P. 13) with the purpose of evaluating the cognitive load of such a device. Additionally, the authors identified that having an AR enhancement on an educational system improved students’ perception of tridimensional aspects, as well as maintaining coherent information between digital and tangible interfaces. Not only that, but the cognitive load that was reduced when these characteristics were applied was significant and complemented Nadolny’s (2017) conclusions on the same subject. Additionally, Al-Imamy (2020) produced a printed textbook blended with AR, but focused primarily on the freedom and versatility that the enhancement provided for students. Majeed and Ali (2020) also focused on an AR approach in the education field, as they sought to address the growing tendencies of the practice in this context. Their research, aided by Yuen et al.’s (2011) overview on AR in an education context produced promising insights into the results of various examples of this approach, mainly through the analysis of different educational methods applied on different studying subjects. This study, and similar research by Kazanidis and Pellas (2019) provides interaction designers with tools to better enhance the projects that seek to blend AR systems in an educational print media context. Furthermore, this concern of the research community also serves as an argument that the pairing of third wave of HCI methods, such as AR, Ubiquitous Computing and others, greatly take into account the multimodality natures of these systems. This is coincident with the recurrent theme of this document, as we have been calling for a material-centered tangible interaction design approach that would better use the multimodality of manipulation, alongside a versatility and a rich array of possibilities of interaction.

2. AI-augmented Interactive Print

A. Autonomous systems and interaction design

Maintaining the focus on the versatility and adaptability of practices that enhance interactivity of traditional print media, autonomous systems pose a stimulating possibility to achieve this. In the current state of AI algorithms, the outlook on the purpose of the field is that of automation, which in some cases is helpful to the good functioning of interactive devices. Recently, with the progress of technological achievements in this context, ML has started to gain considerable traction on research production as a way to contradict the predictability of simple AI (Grudin, 2006). Researchers believe that ML systems will inevitably be intertwined with the HCI scope, while also acknowledging the challenges of that phenomenon (Winograd, 2006). Höök and Löwgren (2021) address this topic by expressing that "Designers — humans— look for correlations and patterns that fit with their understanding of how the world works." (P. 30). This is somewhat contradictory to the AI field as it is data-driven and information based, while interaction design is focused on behavior, mostly between the user and interface. However, ML is a stimulating proposal for integration with interaction design, as its premise is that it "seeks to develop computer systems that auto-matically improve their performance through experience." (Mitchell et al., 1990). In the early stages of ML conceptualization, it was seen as a means for the production of computer software and robotics, as well as possessing problem-solving capabilities. This thought was contemporary with the first wave of HCI context, as users and computers were seen as distant and users were seen as a tool for the software processes. Grudin (2009) addresses that the initial relation of the two fields was mostly competitive, as both required resources and investment to endure and achieve their goals. Additionally, the author details certain periods in which the two areas clashed, but recognizes that in recent years, AI has been introduced in the HCI practice as a powerful tool to achieve positive results. Nowadays, as both HCI and interaction design, as well as the AI and ML contexts have evolved considerably, there is a purpose in researching the possible pairing of the two practices. One of the main questions of this integration, is the contradicting values of the two research topics, as interaction design seeks to provide meaningful experiences to users, while autonomous systems can be seen merely as tools to achieve business goals, with recurrent critics to the application of these on our everyday lives (Höök & Löwgren, 2021). Additionally, Rogers (2006) is concerned with this as she recognizes that Weiser's (1991) concept of "calm computing" is not the present manifestation of Ubiquitous Computing we are interacting with. Autonomous systems have now become invasive and influential to our behavior in a seamless and partial participation of our lives, while Weiser's vision was that of a continuous supply of information. Although this can be seen as an aspect that would negatively influence the HCI practice, interaction designers are the perfect candidates to utilize ML with a different purpose than that of business making and political influence. Höök and Löwgren (2021) add that "interaction designers will continue to serve as catalysts of the ongoing interplay involving human and nonhuman actors, driven by empathy and compassion to care for the human condition" (P. 38). This means that interaction design researchers have a responsibility to correctly utilize autonomous systems as tools to achieve the original goals of the field. To accomplish this, Seidel et al. (2018) believe there needs to be an adaptation in both practices. On one hand, ML might not suit the dynamic and free flowing aspects of interaction design. On the other hand, interaction design practice needs to accommodate computational materials in its interfaces as autonomous systems require specific components for efficient functionality. With this in mind, given the capabilities of ML, we believe that this autonomous system can provide interaction design with stimulating new possibilities of interaction.

B. Machine learning as an interaction design material

Although the integration of autonomous systems in interaction design practice might be perceived as linear in a material implementation perspective, there are other aspects that need to be taken into account. Seidel et al. (2018), addresses design methods that involve development of interfaces. The authors compare traditional interaction design as a double-looped process, as the designer keeps learning from the interface, and responds by adjusting the design of the interaction, through correcting errors or adding features. When ML is introduced in this process, a third influence is part of the development of the interface, as the autonomous system also assesses its functionality, through its own methods and algorithm. This calls for what the researchers believe is the key for unlocking the process, as designers and ML need to be in sync with the principles of one another, resulting in a more balanced interface. To achieve this, designers need to be knowledgeable on the properties and possibilities of ML, much like any other interaction design material. Dove et al. (2017) address this challenge, as they concluded that interaction designers are still inexperienced in this field, but strides are being made to focus on this issue. Moreover, the authors address the same challenge as the previous researchers (Seidel et al. 2018; Yang, 2021), as there is an unpredictable nature to ML systems. The authors agree that designers can approach this by looking into statistical or mathematical methods to carry out interactions, as there can be a dynamic interplay and evolution inherent to autonomous systems. This thought is aligned with Wiberg's (2018) argument, as he believes that the specific characteristics of computational materials are bound to influence interaction design, both in the functionalities of the interfaces, and in its form and meaning. This adds to the tendency acknowledged in chapter 1, in which interaction design is increasingly becoming immaterial and there is a need for interaction design that fosters the physical characteristics of materials. Vallgårda (2014) compares these methods with those inherent to chemistry, as the field is focused on comprehending "molecular structure and responsiveness to other chemicals" (P. 582), while designers are concerned with manipulation of larger scale and of less complexity. The authors (Vallgårda & Sokoler, 2010) go on to identify specific properties present in computational composites: "reversibility, accumulation, computed causality, and connectability" (P. 583). Firstly, this identification allows for designers to not only understand the limits and capabilities of computational materials that allocate ML systems. Secondly, through properties of computational materials, possible interactions can be outlined by a material-centered approach, resulting in a consistent and complete interface. The aforementioned properties outlined by researchers are also relevant to comprehend the possibilities of ML in interaction design, as it provides a support for an evolving and dynamic interaction. This is also made possible by advancements in sensing technologies, as it allows for accessible and precise information-gathering for autonomous systems to assess user-interaction (Gillies, 2019). With this in mind, Gillies et al. (2016) call for a "Human-centered Machine Learning", as the authors consider that designers are shapers of the interface, but through ML, users can also influence the way interaction changes over time. Due to the advancements of technologies related to autonomous systems, researchers believe that there is still much to be made to promote a less restrictive ML approach. Furthermore, they argue that UX designers "can make ML more useful and usable" (Gillies et al., P.2, 2016), through a focus on the values that are inherent to interaction design and HCI practices. Gillies (2019) addresses the challenges that accompany Interactive Machine Learning, as the author acknowledges the increase of high quality sensing devices that are easily accessible and incorporated in various types of interfaces. This prompted the author to look into movement interaction design, as there is a wide array of possibilities to produce stimulating experiences through the dynamic nature of ML. The main output that the user will produce to provide ML with the tools to evaluate and produce feedback is made through interaction with sensors (Villar et al., 2018). This also brings further questions regarding the outlook of computational materials, as sensors are already part of the user's everyday devices: the accelerometer in smartphones for example (Gillies, 2019). With the seamless introduction of these technologies into typical interaction devices, it allows for autonomous systems to have access to a collection of information that can shape the way interaction moves forward. One of the main takeaways of this research is that the main values inherent to interaction design are consistent throughout the whole process, without being restricted to one specific approach. Taking this into account, the multitude of possibilities of interactive ML is especially relevant to this research, as our design process is unlikely to be hindered by material constraints. Moreover, future ML-enhanced interactive proposals can be applied in various contexts of interaction, as ML is versatile enough to be efficient, even if it requires improvements. This provides designers with another layer of producing interaction design that can shape the future tendencies of the field, but also how it can help the development of autonomous systems evolve to accommodate HCI practice.

End Note

As the previous chapter addressed the conceptual mechanics that composed a material tangible interaction approach, in chapter 3, we produced an overview as to what sort of interaction design practice could be applied in this context. The research regarding interactive print media has been stale in recent years, and that is reflected in the lack of references in this section of the document. To contradict this tendency, we focused on how print media is capable of becoming a dynamic support for interaction design mechanisms that have been disregarded by the scientific community. As we argue in this chapter, printed matter is a very versatile and easily accessible material for physical manipulation, allowing for a series of actions that change the properties of the material in stimulating functions. Interactions such as bending, folding, as well as writing or drawing in a simple piece of paper are very particular to this type of material, but are being overlooked by interaction design researchers and designers alike. Given the focus of this dissertation on materiality of interaction, we addressed whether print media can be introduced in a material-centered interaction design approach. This categorization of printed media as an Interaction Design material allows for the pairing of other components to be introduced in the design process. This is an opportunity to pair a fairly simple and accessible material in print media with a very technologically advanced material in autonomous systems, allowing for a coupling of the complementary natures of both. Following this thought process, the chapter focused on looking into research regarding ML and interaction design. The goal was not to explore the intricacies of the algorithms that compose the autonomous systems, but to comprehend how the conceptual nature of this element can become a material for interaction design. The focus of researchers referenced in this chapter was to assess the challenges that accompany this methodology, as they acknowledged the main differences of both fields. One of the main perspectives in this subject is that both interaction designers and autonomous systems need to adapt in order to ease the production of interfaces. In the current state of the research context of both interactive print and ML, we believe that there can still be considerable potential for growth in the references regarding this research topic. This prompted an additional goal for this research, as we hope that the scientific community can be prompted to further explore these concepts. Research produced in this chapter lays the groundwork for our practice-based approach that is carried out in the following section, as the properties, possibilities and limits of AI-enhanced interactive print were outlined.

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Chapter 4. Research through Design

The first chapter acknowledged the theoretical context in which this research is inserted, the second addressed the concepts that involved the practice of interaction design through tangible interfaces and the third focused on the materials that would be the groundwork for the practical development phase. Given this sequence, the present chapter is centered around carrying out of one of the main goals of this research, which was to produce a RtD methodology to acknowledge the possibilities of interaction in AI-enhanced interactive print context. As this research is concerned with the concepts of materiality and physicality as central concepts of the third wave of HCI interactions, we sought to describe the specific methodology that was used in this phase. The process was outlined by the focus on producing RtD, as we find it valuable to provide insights on the practice of interaction design, while still having freedom for generating ideas, sketching and prototyping. This allows for a complete and complementary approach to this challenge, as we believe that this development process can prompt the scientific community to address the lack of both research and projects produced in this context. Furthermore, the methodology was also purposefully described as iterative, even if it is characteristic of typical design practice, as we realized that there could be research insights in the characteristics of each iteration.

A. Design process

“For a long time, design and research have been regarded as separate endeavors”, stated by Stappers and Giaccardi (2017) when introducing RtD as an approach that seeks to produce theoretical output from a practical process. Moreover, Fallman (2007) distinctly separates ’research-oriented design‘ from ’design-oriented research‘ as the two are considerably different regarding the outputs and processes, but also argues that this distinction can help to better define each method. In recent years, RtD has gained momentum in the scientific community, specifically in the HCI context, as Durrant et al. (2017) acknowledge the versatility of practices that utilize this scientific methodology. Goodman et al. (2011) also address the separation between HCI research and design practice, as previous authors have not yet properly comprehended the two aspects of interaction design. The researchers (Durrant et al., 2017 & Goodman et al., 2011) call for a wider and empirical assessment of design practice, as there are several different approaches inherent to the field of HCI. Through the application of this broader method, the research outputs regarding interaction design practices are, firstly, considerably bigger in quantity, but are also more relevant to designers and researchers alike. This approach allows for a more complete description of the theories behind design practice, as there has been a considerable deficit of studies regarding the variations of ’theories of practice‘. Zimmerman et al. call for “interaction designers to make research contributions based on their strength in addressing under-constrained problems” (P. 1, 2007). The authors sought to comprehend how interaction design researchers created outputs, through tools and mechanisms inherent to design practice, from understanding of problems to the execution or prediction of solutions. This resulted in a model that visually expressed several components that are part of interaction design research, as the practice of this field is filled with theoretical and conceptual influences, from various perspectives and approaches. In a later paper, Zimmerman et al. (2010) are still concerned with the definition of RtD as a discipline, as the argument that the lack of descriptive tools for produced research in this context is critical to the correct application of the approach. Dalsgaard (2010) expresses concern on the difficulties of defining interaction design research, noting the multitude of approaches that have been carried out by researchers. The author goes on to argue that "researchers have to be both reflective and articulate concerning their choice of research methods." (P. 203, 2010) adding to the aforementioned need to comprehend different methods regarding RtD. In a more contemporary approach, related to the third wave of HCI context, Giaccardi (2019) addresses the possibilities of a data-driven RtD process. This particular proposition is distinct to previous RtD theory, as the author argues that sensing technologies integrated in design artifacts result in, even if unintentionally, research outputs regarding the use of such artifacts. Additionally, the researcher also addresses the decreasing separation of the definition of 'producer' and 'product', as the sensor-driven artifacts are capable of recognizing ways to better enhance prototypes. As the approaches in design and research are inherently different regarding the process to produce results, Bowers (2012) sees RtD as a method for describing "design thinking in HCI in a descriptive yet generative and inspirational fashion" (P. 68). The author also describes the multiplicity of ways to carry out a process of this nature, as design is an incredibly versatile practice, outlining that the main methodology to be carried out regardless of design approach is the annotation of the design process. Furthermore, Bowers goes on to acknowledge that even if the proposed method is modest in its application, it still allows for the production of "an endless stream of design examples" (P. 77). This endless stream is particularly relevant to this research, as we attempt to address the possibilities of AI-enhanced interactive print, and having a free and dynamic approach to this concern is crucial. Several authors have attempted to produce methods to achieve this goal, Jung and Stolterman (2012) present "form-driven interaction design research" while Stolterman and Wiberg (2010) describe "concept-driven interaction design research". Although the approaches might seem to be of opposing natures, each research sought to address a specific concept that composes traditional interaction design practice. This concern with RtD practice is a positive outcome and a solid groundwork for future interaction design and researchers to build on, moving forward. These differing perspectives on RtD are addressed by Gaver (2012) as he believes that the more methodologies are explored and brought forward, the richer and more varied results will be. This prompted us to attempt to incorporate aspects of each of the approaches and to introduce another layer to the conceptualization of the method, much like was done in chapter 3, in a TUI context. Taking into account the model inspired by Compositional Material Interaction Design (Wiberg, 2018), in Figure 32, that sought to define three steps for development of material-centered interfaces, the following phase was inspired by the Material-Interaction-Manifestation sequence.

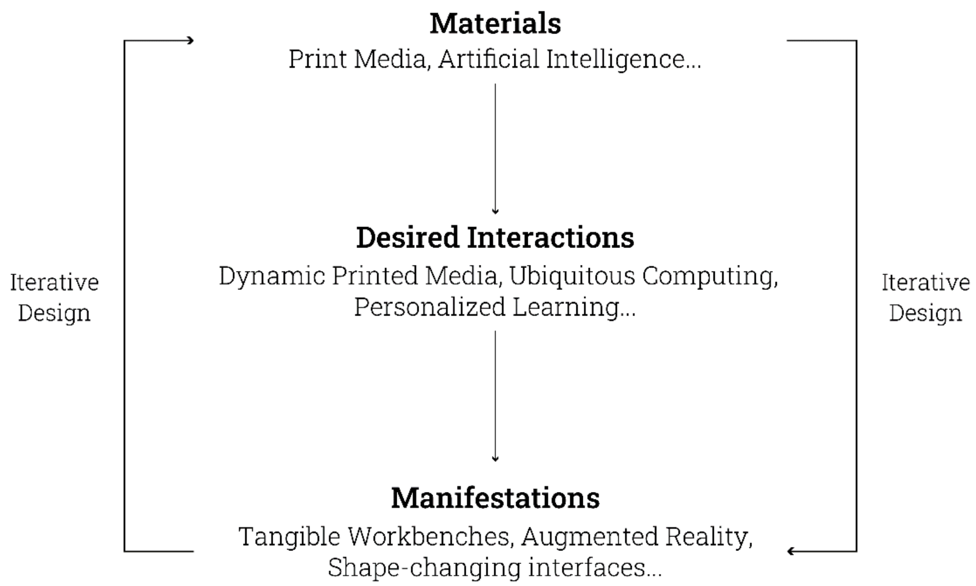


Fig. 32 – Iterative Compositional Material Interaction Design.

Additionally, one of the key characteristics of the process inherent to design is iteration, and to better describe the results of the design proposals we opted to annotate each step of development. To illustrate how this process would be carried out, we produced a metaphor that describes the method in which the research through material-centered interaction design could result in. The Soup Making Metaphor is based on a traditional home cooked soup made with the available ingredients directly from the fridge. Depending on the specific vegetables and components that can be included in the recipe, the final result will vary with the inclusion or exclusion of an element. In our approach, this section is corresponding to the Materials (Fig. 32) as we started by listing the available components and technologies that could be used in this process. With the selection concluded, the next assessment would be that of how the soup would feel and look. With the variations in heat, texture or thickness, the final product would be very distinct from other manifestations, mainly in how it would relate to the people who would taste the soup. In regard to the design process, this is comparable with the Desired Interactions (Fig. 32) as this step would define form, shape and meaning of the interface and how would the user interact with it. With the ingredients and the feel of the soup defined, the possible outcomes are dependent on the manipulation and integration of those aspects, but it does not mean that those manifestations are always going to result in the same soup, or design proposal in this case. Finally, one of the crucial aspects of soup making is tasting, not only in the end but along the whole process, to adjust its characteristics. This is also true for design practice, as we choose to acknowledge the various adjustments that will happen when developing the design proposals. Using this methodology as a starting point, the premise that materials would firstly define the possibilities of interaction, and secondly influence the final product as a manifestation prompted us to define a list of available materials for the project.

B. Sketching

The first step of the conceptualization of this phase was the production of visual configurations to represent available materials to the design process, as it would be fundamental for the following stages. As seen in Figure 33, several sketches were made in an attempt to illustrate and describe the relations between different categories of materials.

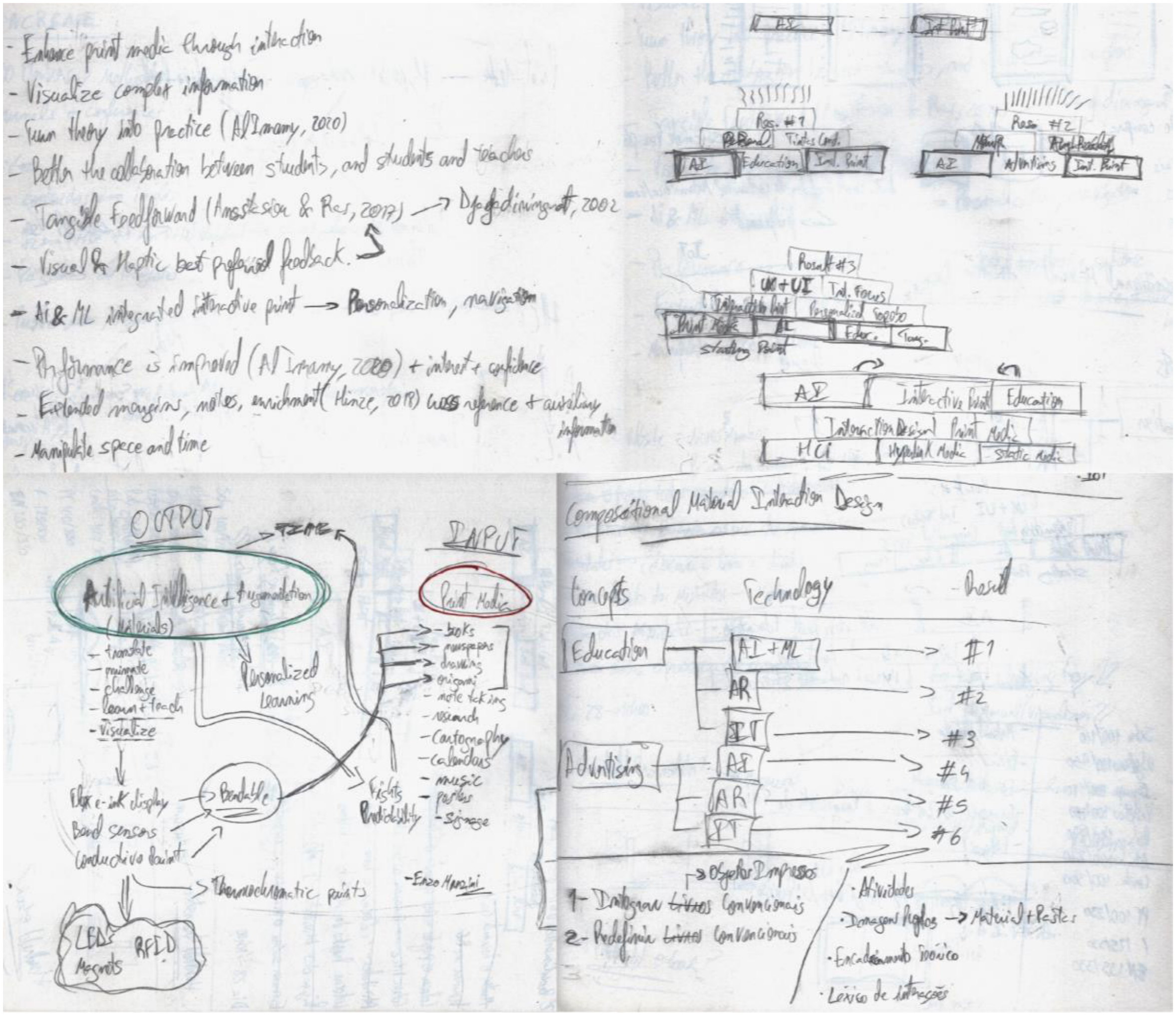


Fig. 33 – Initial sketches of the concepts of research through design.

Firstly, the main concepts that were central to the project were written down to establish the characteristics and possibilities that would be part of design proposals. These were in line with the research goals of this document, as we attempted to incorporate both autonomous systems and interactive print as the main support for the development of design proposals. AI and ML would allow for a much more expansive and dynamic behavior, as it is possible to achieve personalized and enhanced interaction with specific users. From there, the same process was achieved in the print media category, as we provide a list of possible supports that are inherent to the field, as the main starting point for the development process. This step would separate available materials into two categories: Print Media and Computational Materials as these would be the necessary means to achieve RtD goals. From the Materials, the next step would be to identify possible Interactions that media and technology would allow to achieve. As mentioned in chapter 3, printed matter is versatile and easily manipulated, and listing actions that could be carried out was once again, a testament to the richness of this material. Additionally, in this phase, a pairing between the first set of materials and the computational technologies was crucial for the functionality of the prototypes, so that was also taken into account. As the integration of print media and computational materials was addressed, the enhancement of the interface through autonomous systems was left as an open-minded aspect of the scheme. Finally, with the two first lists of components being established, it was then that the third and final step of the process would be achieved. This is the phase in which we started conceptualizing possible manifestations for the design proposals. This was fulfilled by the pairing of materials and interactions with the closest capabilities. For example, connecting bend sensors and flexible e-paper displays with interactions based on bending and folding allowed for a straightforward relation. This process proved to be successful as it resulted in several design proposals, with mostly different concepts and contexts of interaction, that were described in the following section of the document. The scheme of the process can be observed in Figure 34.

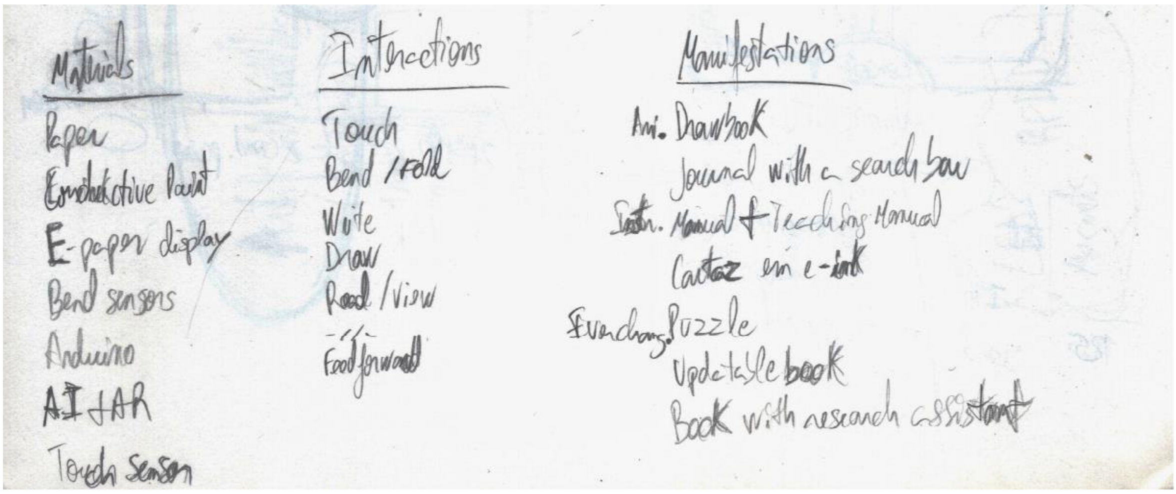


Fig. 34 – Initial sketch for the development of the design proposals.

C. Design Proposals

As the methodology and main structure for the development of the RtD were defined, the following phase was dedicated to the experiment of different paths for possible manifestations of devices. This resulted in a process that sought to identify relevant interfaces in an AI-enhanced interactive print context. Initially, this was hindered by an overwhelming quantity of possibilities that could be identified, given the versatility of the materials that were inherent to the research. As mostly any device can be enhanced with autonomous systems by the integration of computational materials in its conception, the definition of concepts came through actions that are related to printed matter. This unlocked the initial difficulties, as it prompted a much more dynamic outlook into concepts of manipulating the manifestations. Desired interactions such as drawing, writing, and folding were crucial for this exploration, as these actions sought to take the most advantage of the proposed materials. This allowed for ideas to be merged into others, creating a free-flowing environment while still maintaining the same goal and groundwork, due to the initial structure before the development. Following the initial focus on the creative aspect of manipulating print media, we turned to reading and to viewing devices as physical objects with tangible manifestations. This was relevant as the research has a tangible interaction background and channeling those concepts would allow for design proposals with multimodal manipulation regardless of its manifestation. Then, with the integration of computational materials, the iterations of the proposals became much more robust and feasible, as they were given shape and another layer of dimensionality. Throughout the whole ideation process, the proposal influenced each other, as we believe that the development should be seen as a whole and through an outlook of different perspectives, each concept was complemented by this approach. Therefore, the following section describes design proposals that were chosen to be part of RtD (Fig. 35).

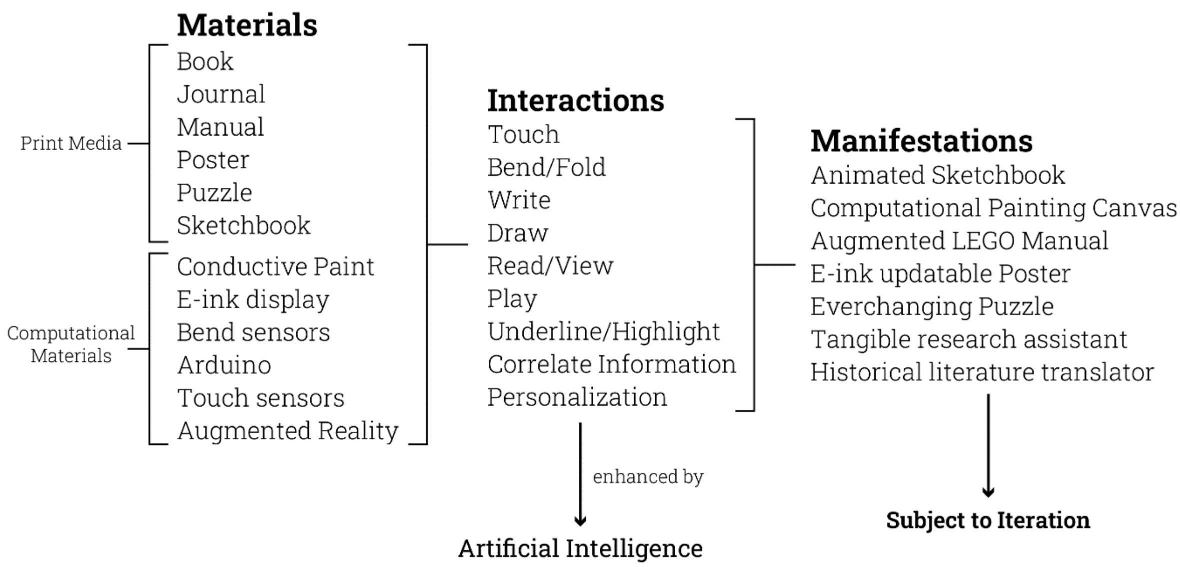


Fig. 35 - Final structure for the development of the design proposals.

1. Animated Sketchbook

Taking into account the versatility of a sheet of paper, producing a device that would allow exploration of that property was seen as a stimulating opportunity. In an attempt to distance interactive print practice from a point-and-click based interface, the purpose of this system was to animate a simple drawing. Inspired by typical children's drawing, the project would allow for an exhibition of the rudimentary art to still have a physical manifestation, as to be placed on a fridge or in a class project, for example. With the idea that it would bring drawings to life with the help of AI, we sought to define interactions that would compose the interface. The first section of the experience is the manual Drawing, in which users would be guided to draw the segments of a visual composition - this would allow the computational component to recognize different modules and animate them later - such as the head, body, and limbs, as well as background, landscape and additional elements. Following that phase, after the drawing is concluded, the user enters the Game section, in which autonomous systems will both recognize the drawing and animate the composition with simple, linear animations, as seen in platformer games, such as *Super Mario* and *Flappy Bird*. The process is described visually in Figure 36. With only the need for running and jumping animations, the premise of bringing simple drawings into a playable experience showed promise. Not only that, but introducing autonomous systems in this context would allow for yet to be seen experiences. AI would be responsible for the recognition of the different segments of the drawing as well as the animation of each of them, while ML would evaluate user's gameplay and adapt the difficulty to bring an easier or more challenging experience.

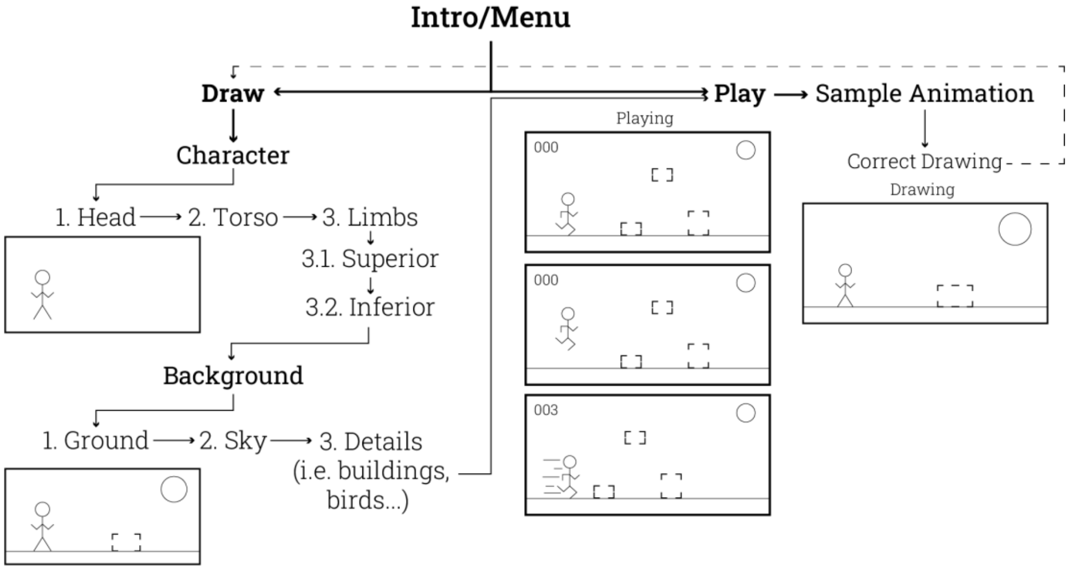


Fig. 36 – Animated Sketchbook Interaction Map.

After the definition of possible user tasks, the following phase was the development of the possible manifestations that would be able to support this experience. Although initially the interface was seen as a vertical book, in which in one page, users can have access to the detached singular paper sheets to draw in, while the gameplay and animation will occur in the opposing page, as seen in Figure 37.

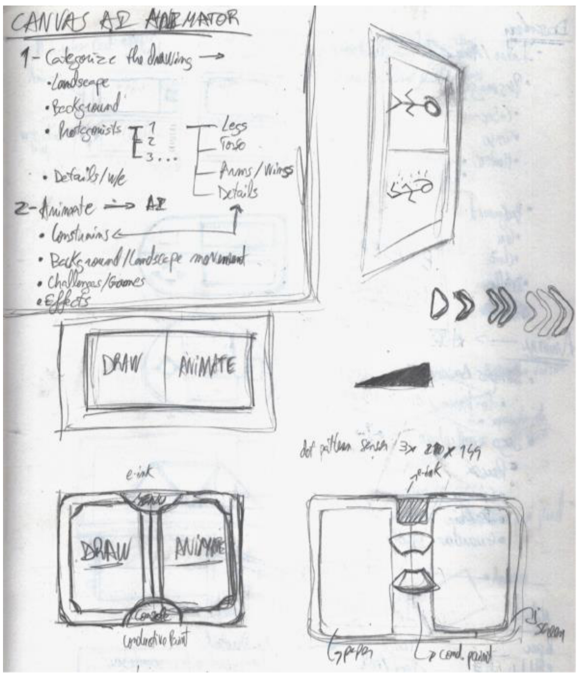


Fig. 37 – First Sketch of the Animated Sketchbook interface.

Realizing that the most typical orientation for platforming games is horizontal, as well as being the one usually used by children while drawing, the following sketches showed a shift in the interface structure. With this change, the device was drifting away from the original aspect of a book, which would improve the aesthetic integration of the computational materials that would be required. Therefore, it was seen as a goal to explore different models and structures for the interface, as it had now become similar to already known game consoles, such as the *Gameboy Advance* and the *Nintendo DS*. With that in mind, there was an effort to explore the possibilities of a more traditional console, not only in overall configuration, but in its aesthetic and functional callbacks to print media materials as well, such as sketchbooks with rings, allowing for a scroll through drawn pages, as sketched in Figure 38.

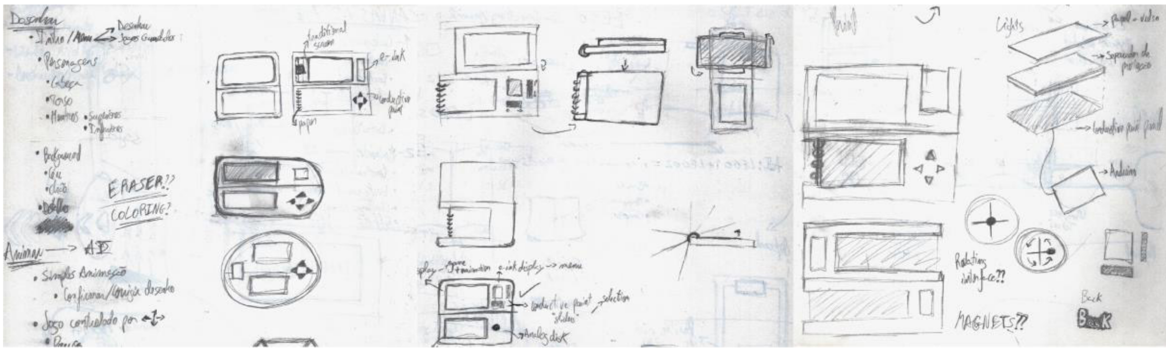


Fig. 38 – Ideation process of the Animated Sketchbook interface.

Although the physical aspect of the interface was not yet defined, the initial four components that would compose it were established as the foundation for this proposal. Firstly, the system would require a drawing panel that would be composed of touch sensors to recognize the drawing made on a separate sheet of paper; then, a screen in which the animation and gameplay would take place; thirdly, a console with movement buttons to both interact with the game, and to also navigate and confirm menu options; and, finally, a e-ink display in which the menu and feedback would be present, separately from the gameplay screen, to accompany the user in real time, as seen in Figure 39.

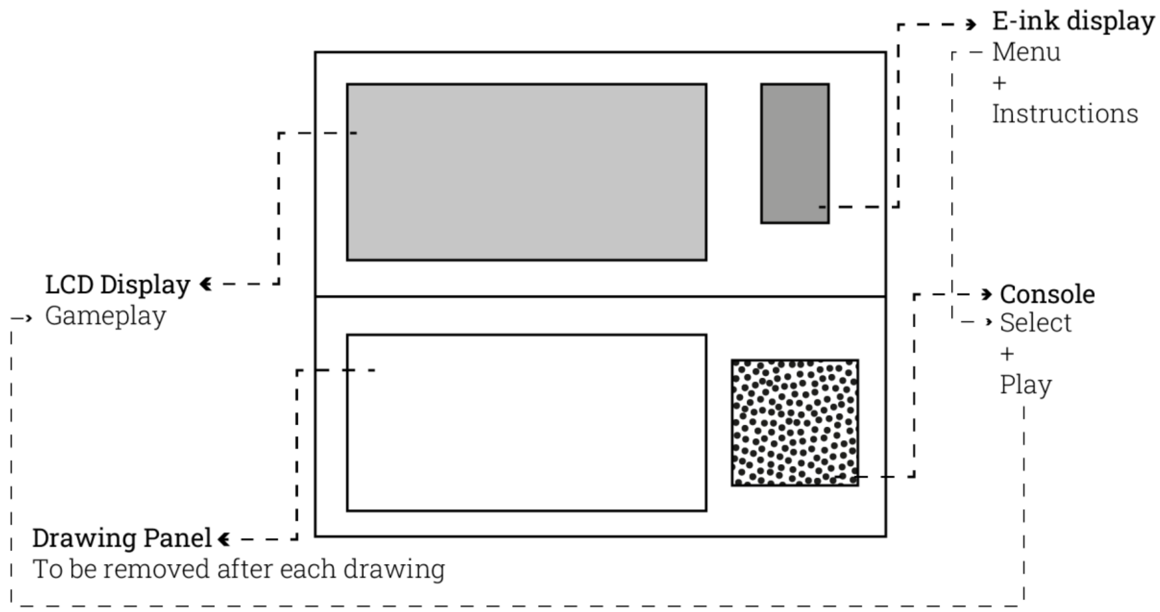


Fig. 39 – Components of the Animated Sketchbook interface.

Simultaneously, taking into account physical constraints of computational materials that would be required to execute the recognition and animation of the drawings, a rudimentary scheme was made, to better visualize the drawing panel component, as it would be the most challenging to prototype. The top layer would be a sheet of paper, in which users would draw as they would normally, allowing for it to be removed and replaced, below it, there would be a protective tab, that served as a base for the page to be on, and as a surface to maintain the integrity of the lower layer, the conductive paint panel with the purpose of recognizing linear drawings made in the topmost layer, while being integrated with a printed circuit board, in which AI would reside. In addition to the proposal for the Drawing Panel, a simple 3D model and rendering were made to assess the materiality of the device, as shown in Figure 40.

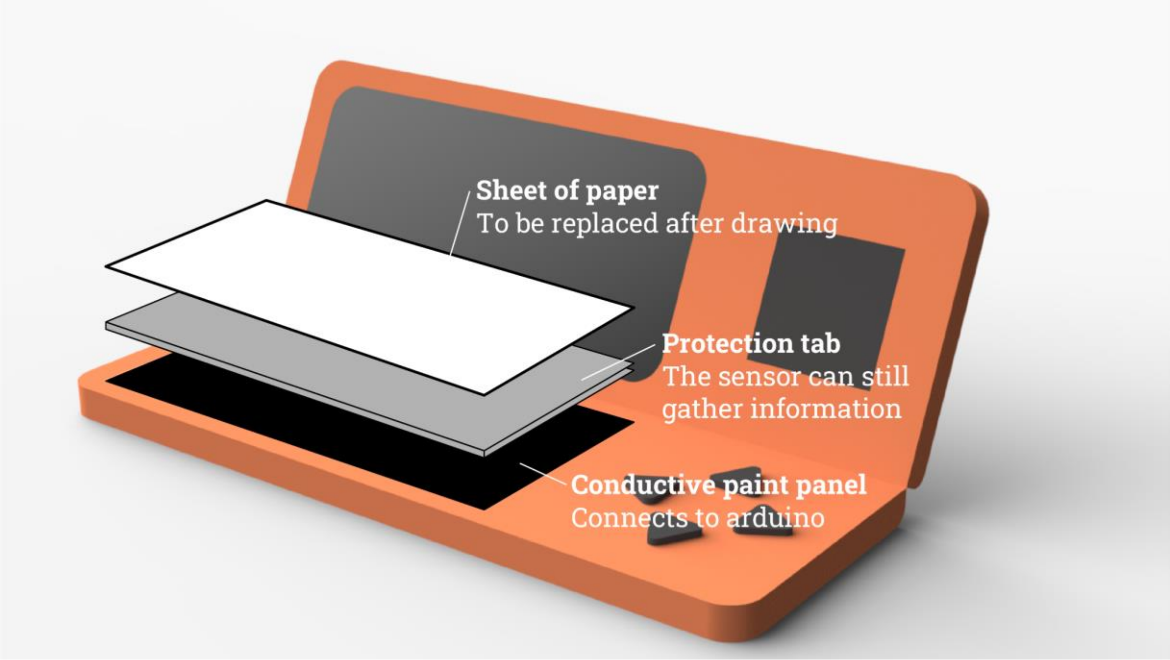


Fig. 40 – Animated Sketchbook Render and Drawing Panel scheme.

As the shape of the device was explored, the following iterations focused mainly on the influence of Autonomous Systems regarding the gameplay experience. AI would have the purpose of recognizing the drawing, animating it through premade vectors, as well as gathering gameplay information such as time of playing or points obtained, and errors made by the user. With this information, ML could understand the difficulties of the user regarding the challenges presented, be it through a quick succession of obstacles, or through the scale of them.

In the future, revisiting this proposal would be focused on the shape of the interface, as well as defining a more integrated interaction, as it can still benefit from a deepening of the user actions and system reactions.

2. Augmented LEGO Manual

The second proposal came from the smartphone application “Brickit” (https://brickit.app), that through AI, can recognize LEGO bricks in bulk, dispensing the need to organize them. As well as identifying each brick by color and shape, the app also provides a catalog of pre-made constructions that can be made with the bricks that were initially collected. This was a stimulating premise that would drive forward the creation of an augmentation of this basic interaction of recognizing and building. As this research is focused on an Interactive Print approach, finding a way to experiment and enhance the well-known blue physical LEGO building manuals was the starting point. So, with the print surface defined, and with the AI capabilities in mind, the challenge was to integrate and produce a stimulating experience. Initially, the proposal was merely a set of small e-ink displays that could be placed on top of an already existing manual and would orient the users dynamically with feedback to each construction step (Fig. 41).

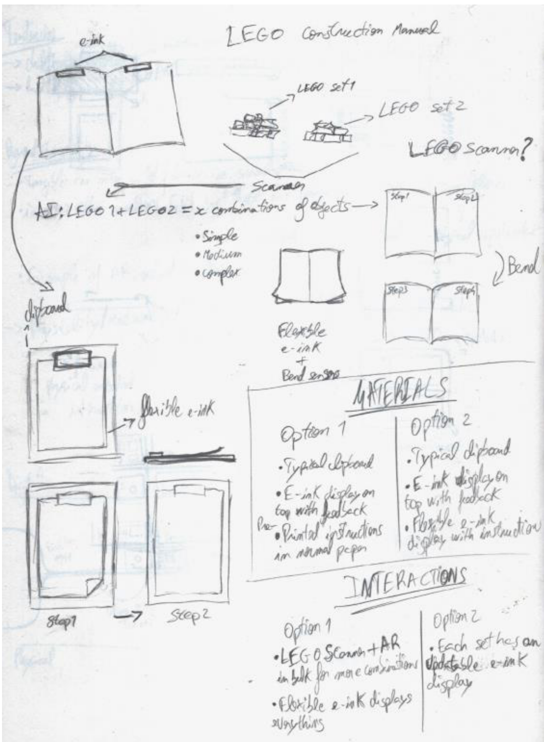


Fig. 41 – Augmented LEGO Manual sketches.

That iteration was quickly scrapped and the proposal took a more material shape. The manual would now reside in a single sheet of flexible e-paper, with a clipboard in its support and a device on the top, that would be responsible for AI and AR functionalities. Additionally, the planning of how AI would recognize each brick and produce corresponding building possibilities was being thought of. As figure 42 denotes, two options were determined to compose what the interaction would be based upon, one that sought to mainly augment already existing manuals, by integrating them with a clipboard and e-ink display as previously planned; and another that wanted to take the full capabilities of AR and AI.

	Iteration 2.1	**Iteration 2.2**
Materials	- E-ink display on top with menu and feedback - Printed instructions on typical manual for each set - Interaction is made solely by building the set	- E-ink display on top with feedback - Flexible e-paper display with instructions for any set - Interaction is made by physical manipulation
Augmentation	-Each set has an instruction manual that can be integrated with the clipboard	- LEGO scanner that analyses existing bricks with a camera/RFID - Instruction manual can integrate any brick and set
	↓ Lacks physical and digital manipulation, the feedback from the display will enhance the building process	↓ Allows for new combinations between LEGO sets, recognizing pieces that are not identified and a more free experience + With a scanner that identifies LEGO bricks, the manual can include a AR mechanic to 3D visualize the desired construction

Fig. 42 – Scheme for the comparison of the interaction options.

As seen in Figure 43, the manual would digitally represent each step of the construction with dynamic feedback; the topmost component would be a scanner for the AI to recognize each brick, as well as AR camera for the tridimensional augmented visualization of the proposed construction; while finally, the support clipboard would integrate and connect the computational materials required for this interaction.

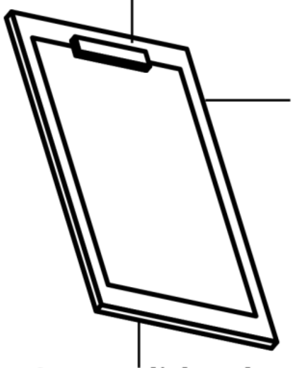


Fig. 43 – The components of the clipboard-supported manual.

In this phase, to make sure that the versatility of AI is utilized to a greater scope, it was hypothesized that this autonomous system could produce a greater variety of building proposals, through an algorithm that did not require human intervention. As the Brickit app exemplified, there can already be a relation between random bricks and already made combinations of buildings, but, as AI evolves and allows for freer flowing and creative capabilities, there can be an opportunity to go further in this context. Additionally, LEGO sets are typically themed for a brand or a specific type of builds and that is an important characteristic for users to approach an item, losing that pulling point would be a negative aspect of the AI-enhanced manual. We argue that when a customer buys a LEGO Star Wars set, for example, it is expected that the build will eventually end in a Star Wars model, but AI and ML could produce combinations of these sets, allowing for not only one end product, but an “infinite” number of them. Not only that, but this proposal can also result in the production of mixed sets, as a Star Wars build could integrate elements from Harry Potter, for example, broadening the scope of constructions even more. This can also give users more value for each of their buys, as it would mean that each set would not only bring one singular product, but an increased amount of it. With the increase of focus on AI-enhancement, a return to the interface was made, as its shape and support was recognized still as too conventional, as a clipboard with a sheet of paper would not push the material interactive print approach forward. In order to answer this concern, the proposal maintained the flexible e-ink and AR plus AI components, while the clipboard was removed, and its alternative resided in the users' own builds. As mentioned before, AI would give users combinations of sets for building as it is the main purpose of the sets, but it is proposed that users can also influence the shape of the interface by constructing it themselves. The builds would have to be able to integrate the components of the manual, but it could mean that bigger sets could implement the interface easily (Fig. 44).

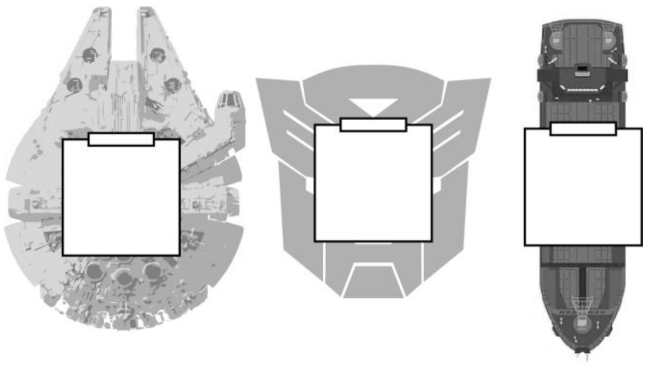


Fig. 44 – LEGO Manual integrated in large scale builds.

As the interface iterations were evolving, the ML interventions were simultaneously being thought of, as the AI would recognize the LEGO bricks and then propose combinations of builds depending on those same components. This is where ML can be introduced, if AI can obtain information on the preferences of buildings for each user, depending on scale, difficulty, associated brand, color, and so on, ML can produce a set of combinations that go according to the users' liking. This can foster a creation of user profiles, as different people can use the system, and the device will generate possibilities for each specific person. Not only that, but as the e-paper sheet is digital, autonomous systems can also recognize difficulties and tendencies while building for each user, therefore being able to adjust the steps for a more comfortable and enjoyable experience. Despite being a favorable enhancement, the purpose of introducing these augmentations is not to provide the user with the answer without challenge, as the reward is not only in achieving the final product, but overcoming each difficulty fosters a more beneficial experience.

In the future, return to this proposal would require a shift in the approach for the interface, as it still needs reflection in how the support can evolve from being merely a bidimensional display without yet being defined how it would differ from a traditional smartphone or tablet interface.

3. Everchanging Puzzle

The core idea of this proposal has always been the thought of a puzzle that would change with every move or session, creating an infinitely challenging entertainment system. Initially seen as a typical art or landscape jigsaw puzzle, the objective would not be to fit in every piece but would be to combat the randomness of the challenges brought by the device. As exemplified in Figure 45, the first iteration was a tabletop board, that would randomly replace and rotate the hexagonal pieces and the user would have to put them in place, and when that was done, there would be a new picture for solving.

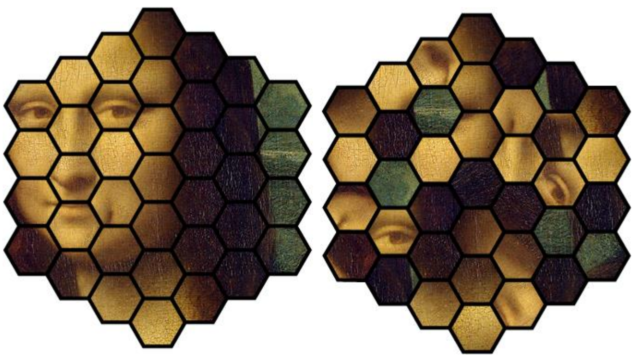


Fig. 45 – First Iteration of the Everchanging Puzzle proposal.

As the interaction was deemed too simple and as it was demonstrated on previous proposals, would not add another dimension to the already existing jigsaw puzzles, so it took a path for a more objective-oriented and feedforward approach. As the initial iteration was based on the hexagonal shape, the following prospects took inspiration from well-known board games, such as *The Settlers of Catan and Hex* while also looking to give the type of challenge that the slider puzzle offers users. This produced a richer concept that would firstly add another aspect to the board initially presented, as it could take the token-based approach and enhance it with autonomous systems. Additionally, exploring the materiality of a tabletop board would also be stimulating as a third, vertical dimension could be added for the user to explore without the restraints of a digital media. While still maintaining the hexagonal shape as a central piece, the main goal for the game was that the whole human action would be made through a single piece, without needing console elements, such as knobs or buttons to accomplish the puzzle objective. As the point of removing physical controllers was made, there needed to be a component that the users would have full control over, that would dictate all the interaction of the puzzle-solving attempt. The goal of the puzzle is to bring the S piece, for Start, into contact with the E, for End. As it is demonstrated in Figure 46, the puzzle is composed of two highlighted (the colors are merely demonstrative) hexagons, the S piece is slightly elevated over the rest of the pieces and is the only one that the user will move; and the E piece that will be lower than the rest of the board so that when the S piece is moved towards it, it can fit into one, completing the challenge. When they are connected, the E piece will elevate to be in line with the rest of the board, and another piece will then take its place as the end goal of the puzzle.

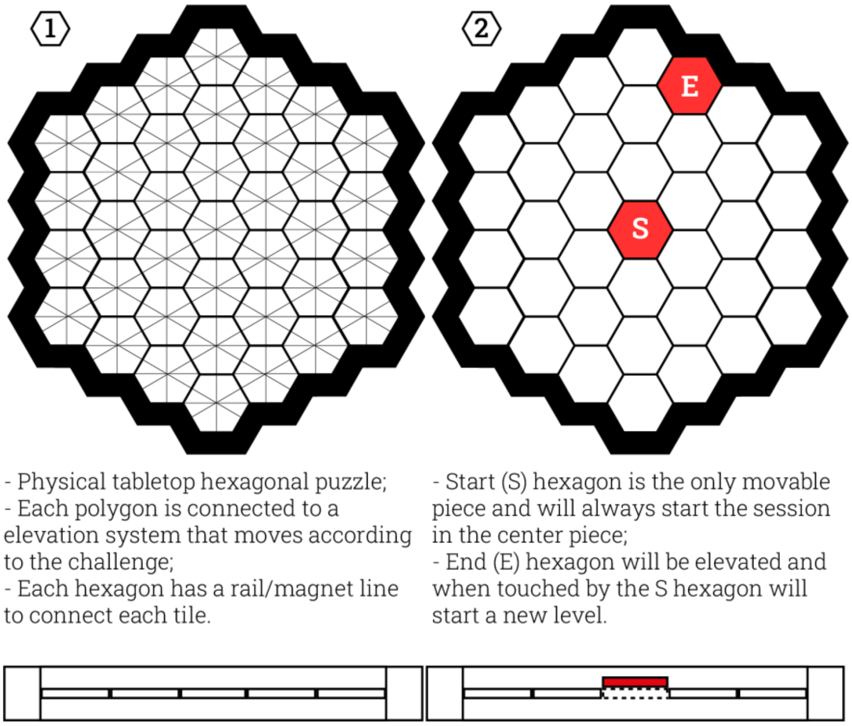


Fig. 46 – Everchanging Puzzle composition.

Additional attributes for different pieces were also predicted so that the challenge would be more challenging, such as depicted in Figure 47. For example, having hexagons that would rise over the rest of the board to make it so that the path to reach the End piece would be less linear and would require more thoughtful planning.

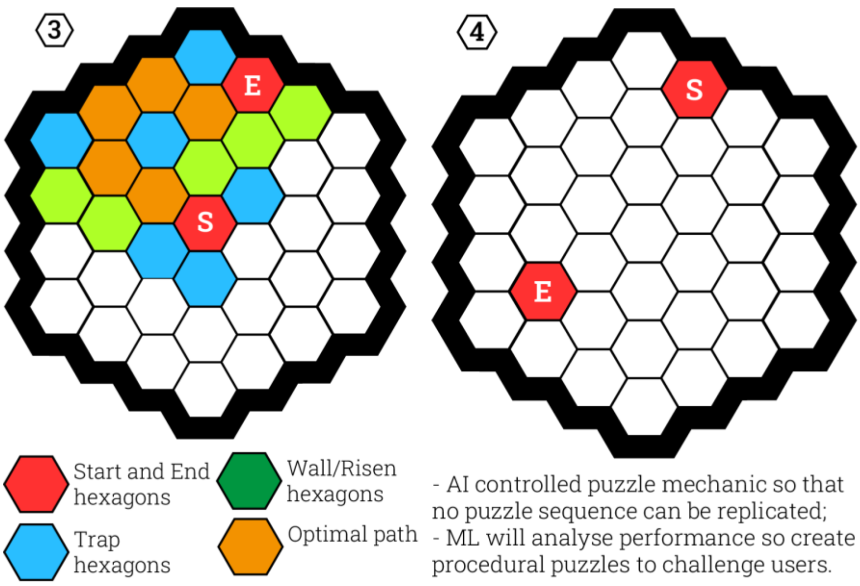


Fig. 47 – Everchanging Puzzle composition.

This proposal had the inconvenience that as hexagons are shapes that possess 6 sides, traversing the board in 60º degree angles, would be problematic if there are two adjacent wall hexagons as the edges would not permit for the oblique movement, as demonstrated in Figure 48.

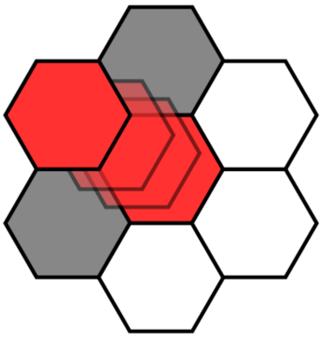


Fig. 48 – Hexagon pieces collision.

Although it might be seen as an issue for the user to navigate this problem, if done correctly, it can pose a challenge, as it is still possible to produce challenging puzzle levels without impeding the movement completely, with a careful planning of the game-making mechanics. This would mean that users would have to realize that their transversal path would have to take into account this simple constraint.

With this in mind, a 3D model of the board was produced and animated to acknowledge the potential of two possible levels of the puzzle, as depicted in Figure 49. In the first segment, the movable piece is raised over the rest of the board, and as the puzzle starts, the rest of the pieces shift in height to orient the user on the proposed challenge. Then, as the highlighted hexagon reaches the opening for the conclusion of the level, the board resets so that another puzzle can take place, with a different configuration. This is AI and ML influence the interaction. The responsibility of producing the layout of the puzzle is on AI, as it will map the challenge automatically, while taking into account the physical constraints previously mentioned. Not only that, but the autonomous systems will evaluate the user's performance so that their difficulties are assessed, depending on the time taken to achieve the desired result, or by number of errors made in the process. These metrics will allow for ML to comprehend the users' behavior and adjust the challenge so that the user is not approached with an impossible task or a very simple one.

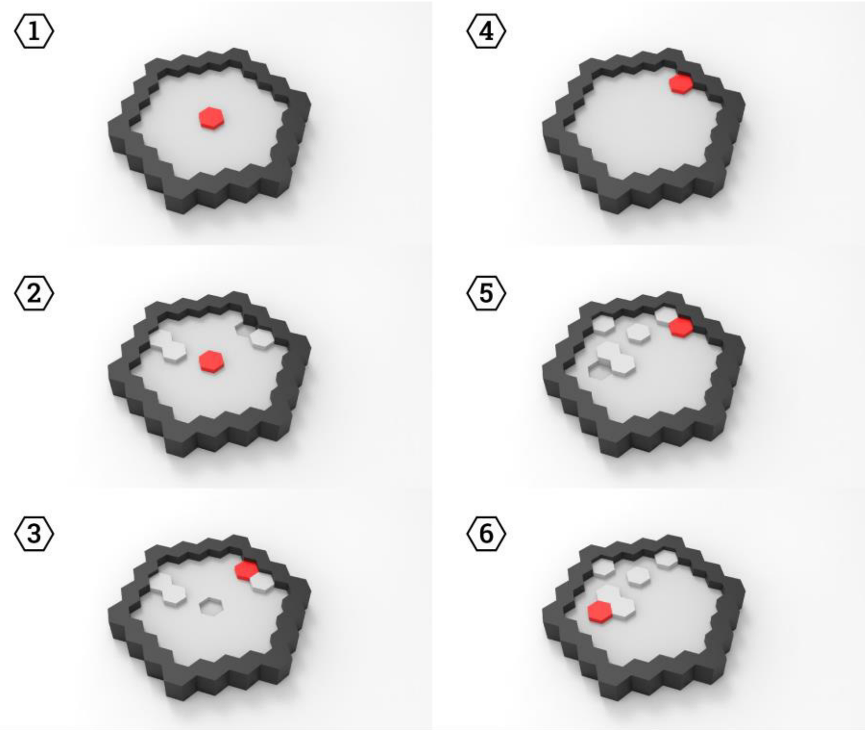


Fig. 49 – 3D model of the Everchanging Puzzle.

This proposal sought to manifest the capabilities of manipulating print media as a tangible manifestation that has the possibilities of encompassing a great amount of different tasks. Therefore, with simple mechanics of moving and preplanning the solutions of the different levels, similar to the manipulation in a jigsaw puzzle or a *Hex* tabletop game is not only promoted, but also enhanced. With the integration of this puzzle scheme and the autonomous systems, the premise of the everchanging puzzle can be achieved, as the number of combinations and challenges that can be produced will be considerable. In the future, the proposal can also introduce timed challenges, different user profiles, so that there is a long-term use of a simple concept, bringing piece S to hole E.

4. Computational Painting Canvas

Following the same concept of the Animated Sketchbook, this proposal sought to approach the dynamic and artistic possibilities that reside on print media and enhance it with computational materials. In a context in which paintings and photographs created by AI are creating an uproar in the artistic communities, as some believe that those practices are reserved only for humans, this can be an opportunity to create new forms of interaction based on this integration of art and autonomous systems for another proposal. With this in mind, the concept for this proposal would not be to create art through AI, but to enhance the process of painting, through dynamic and responsive properties of computational materials, making the best of the expressive nature of artistic creations. With the painting canvas as the starting point, initial sketching led us to create a tabletop system in which the canvas could be integrated and augmented by other types of manifestations (Fig. 50). The considered possibilities were expressions such as a LED sequence that would follow the brush movement and colors, or replicate imagery with different filters and adjustments

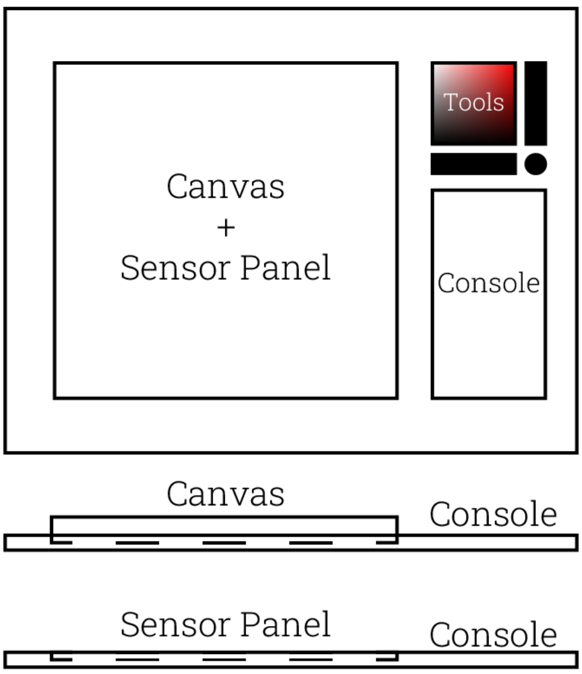
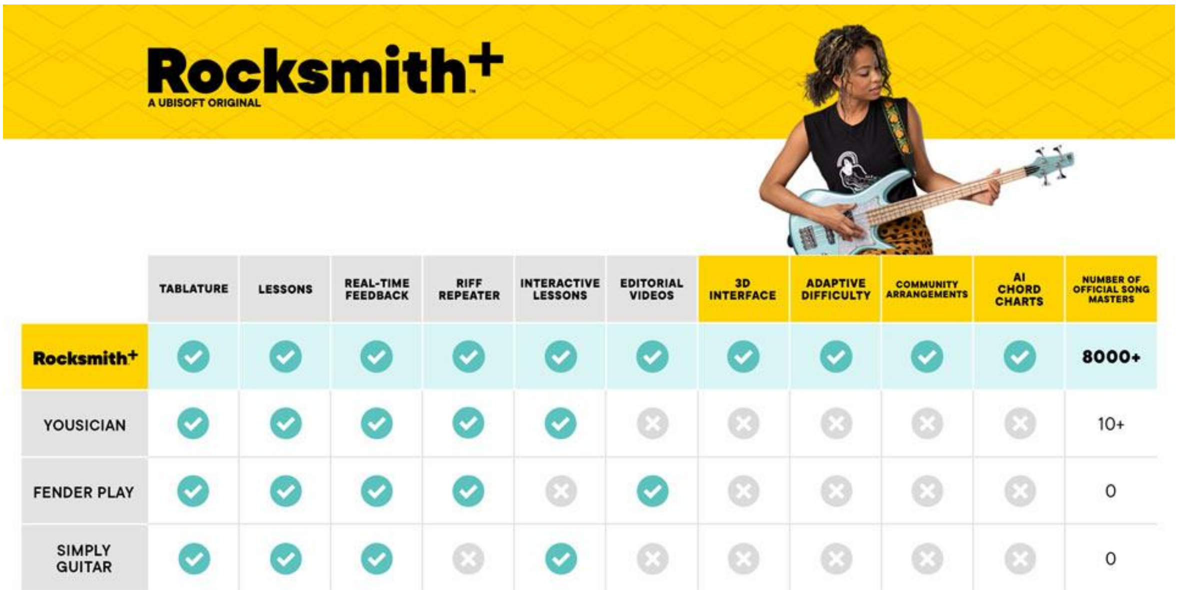


Fig. 50 – First iteration of the Computational Painting Canvas.

We recognized that the device would not augment the painting experience but would mostly create a small number of interactions that would deviate from the value of artistic expression. Therefore, a second iteration was based on integrating an interface on a typical painting easel, as it is the most commonly used support for painting, albeit of very simple design and of static nature. This promoted an opportunity to add a dynamic system that served to accompany users as their painting process took place, without jeopardizing it with out of context distractions, as previously mentioned. Additionally, the opportunity of providing a guiding instrument to give learning tools to users of different experience seemed like a possibility to augment the interaction even more (taking into example the Rocksmith+ game in Fig. 51).



	TABLATURE	LESSONS	REAL-TIME FEEDBACK	RIFF REPEATER	INTERACTIVE LESSONS	EDITORIAL VIDEOS	3D INTERFACE	ADAPTIVE DIFFICULTY	COMMUNITY ARRANGEMENTS	AI CHORD CHARTS	NUMBER OF OFFICIAL SONG MASTERS
Rocksmith+	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	8000+
YOUSICIAN	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	10+
FENDER PLAY	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	0
SIMPLY GUITAR	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	0

Figure 51 – Rocksmith+, an Interactive Music Learning service for guitar and bass, that offers Real-Time Feedback and Adaptive Difficulty for users with different levels of experience playing the instruments. Source: Ubisoft, 2021.

With this in mind, another set of sketches were made as to how computational materials could add to the painting experience without interfering with its artistic manifestation (Fig. 52).

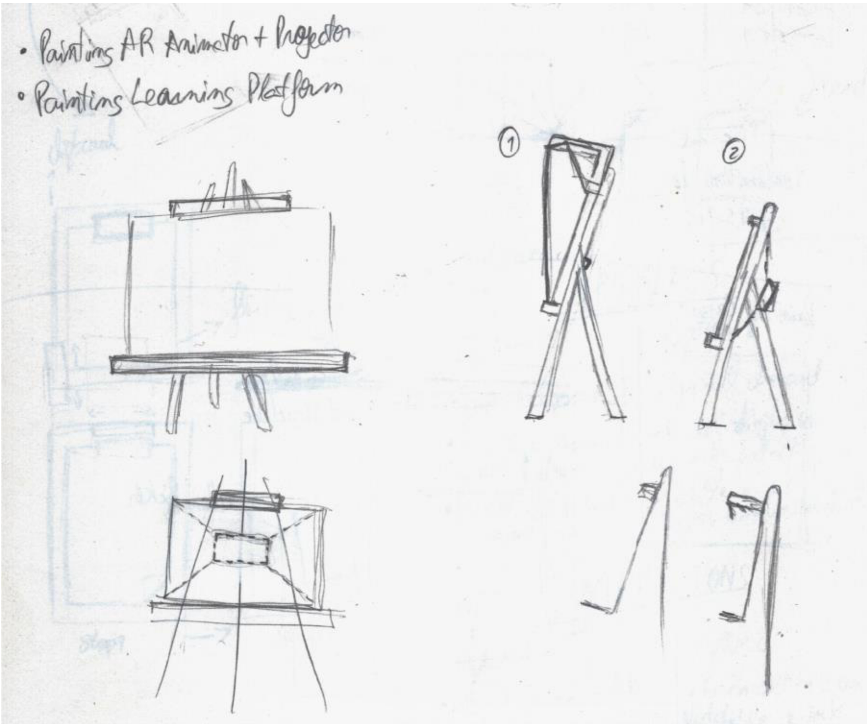


Fig. 52 – Sketches for the second iteration of the Computational Painting Canvas.

As the sketching process sought to assess the possibilities of how an interface would integrate the easel without hindering the painter, a projection digital device seemed the most appropriate, as it could dynamically adjust the information according to user's actions. Not only that, a scanner or sensor could also provide the projector with information on the painting progress, as lines would be drawn, or shapes filled with color. This thought process and sketches evolved into a more mature representation and definition of interactions.As represented in Figure 53, the device was composed of a projector and scanner that would be attached to the easel, in order to both collect and provide information regarding the painting experience.

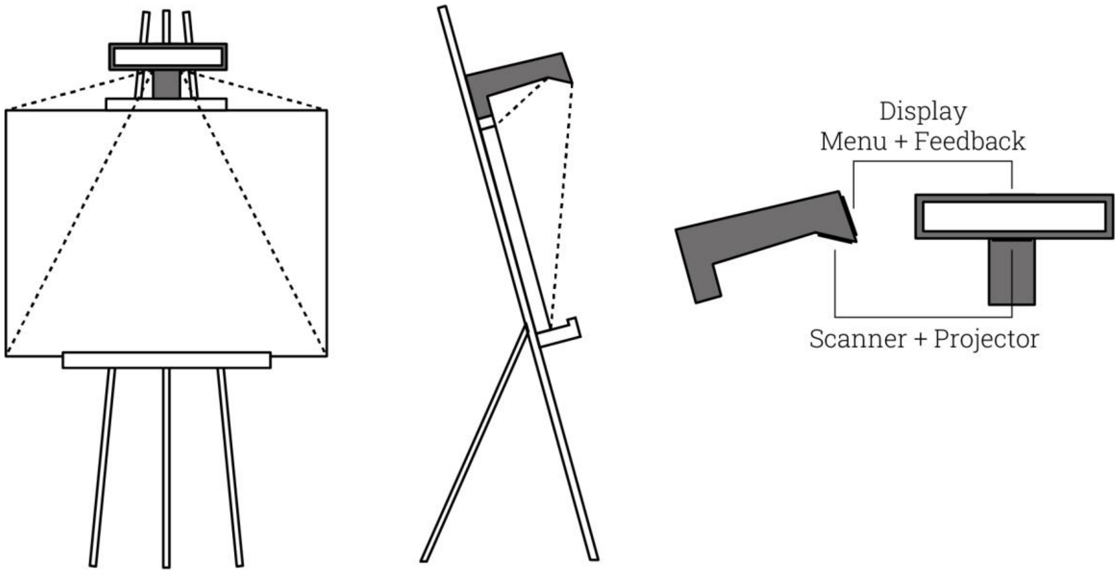
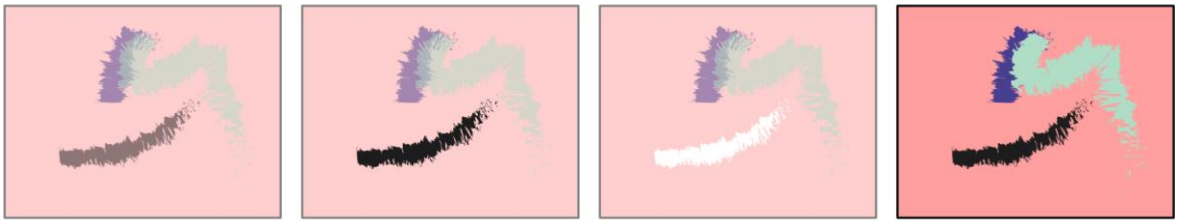


Fig. 53 – Representation of the Computational Painting Canvas.

Firstly, there would be a digital interface that would possess a menu for customization and enhancement of the process, depending on user's preferences and needs; then, a projector that would provide digital tools for the painting process, such as original images for inspiration, guides and grids for the framing and placing of elements, or a learning assistant that would present the user with additional information or specific brush movement or color mixing so that the user can gain experience through it. At its core, this proposal is an AR system, as the different sizes of canvas would be the markers for recognition, and the projection would be the digital manifestation of the information. We once again sought to have a seamless integration of the painting process and AI-enhancement, and a small device of this nature would provide with such materialization. With the definition of the physical manifestation of the proposal, the following step was to plan the purpose of the AI and ML on the project. With the existing scanner, the Computational Painting Canvas could recognize the user's painting behavior, as their experience and personal expression can vary, as well as their preference for specific original imagery. With that information, ML could dynamically adjust the projection to provide a positive guide to the user as to their progress both in a specific painting and in their learning experience. AR projection of the original inspiration or photograph can also be responsive depending on the user's painting method, as the canvas is being filled, the representation can be faded out in that specific area, as exemplified in Figure 54.



AR setup | Painter uses black brush | AR Removes segment from original setup | Final result

Fig. 54 – Example of dynamic AR representation of the original painting.

In this proposal there is also the concern that ML integration might result in the device providing the user with too much information, removing personal learning experience required for a gratification of overcoming challenges. With this in mind, we argue that if autonomous systems are calibrated for this purpose, there can be a selection of conditions that do not allow the information to hinder the painter's process.

With this proposal, we would like to better represent the possibilities of AR and how it can respond to different users' behaviors, as well as the definition of digital manifestation of the interface, mainly the menu and feedback functions.

5. Tangible Research Assistant

As the literature review was being produced, simultaneous with the RtD process, reading made through physical books was the most enjoyable, but the difficulty of bridging information gathered from books into this document was a concern that could provide an opportunity for a design proposal. Typically, as reading is not usually done close to a personal computer, users can be accompanied by a journal or a notebook in which inputs from research can be written or directly underlined on original books. As our research went on for several months, and notes had been made for various topics, we found ourselves wondering as to the possibility of having a 'Control + F' finding command on a physical journal or notebook. That concept is what prompted the first ideation of the proposal, as it did not need to be a very intrusive device, requiring only a capability of adapting to different sized books, to provide a more integrated research process. As Figure 55 depicts, initial sketches had the goal of producing a device that would not change the configuration of original reading material, as well as possessing a seamless integration with it.

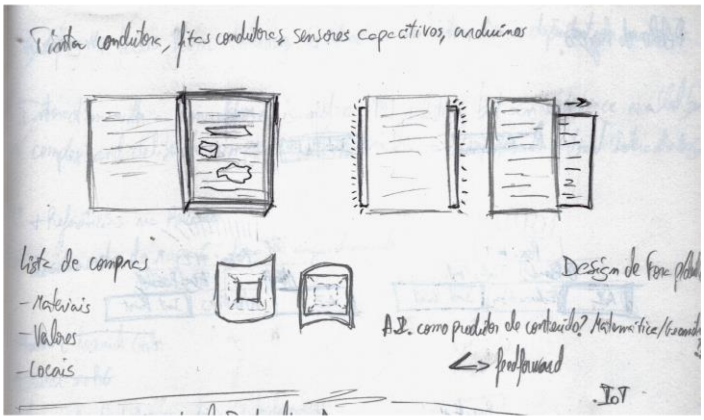


Fig. 55 – Initial Sketches for the Tangible Research Assistant.

Recognizing the challenge that would be presented if the device was available to every book, the concept shifted so that only research publications were the chosen print media. Taking into account the needs inherent to reading and writing research, this would not be detrimental to the interface, as there are still interactive opportunities to tackle in this field. With possible capabilities of saving text segments as quotes for further review, selection of figures and tables to reference in the research document or a search engine that provides a list of related references to that of the original book. These propositions made for the main tasks that would compose the interface, as the physical properties of the device were being thought of simultaneously. The purpose of the system would be not to influence the copy of printed books, as the typical ways to highlight and annotate text on these objects are actions that affect its integrity, but to augment the information relevant to the user. As seen in Figure 56, both the possibilities of interaction and the manifestation of the research assistant were sketched.

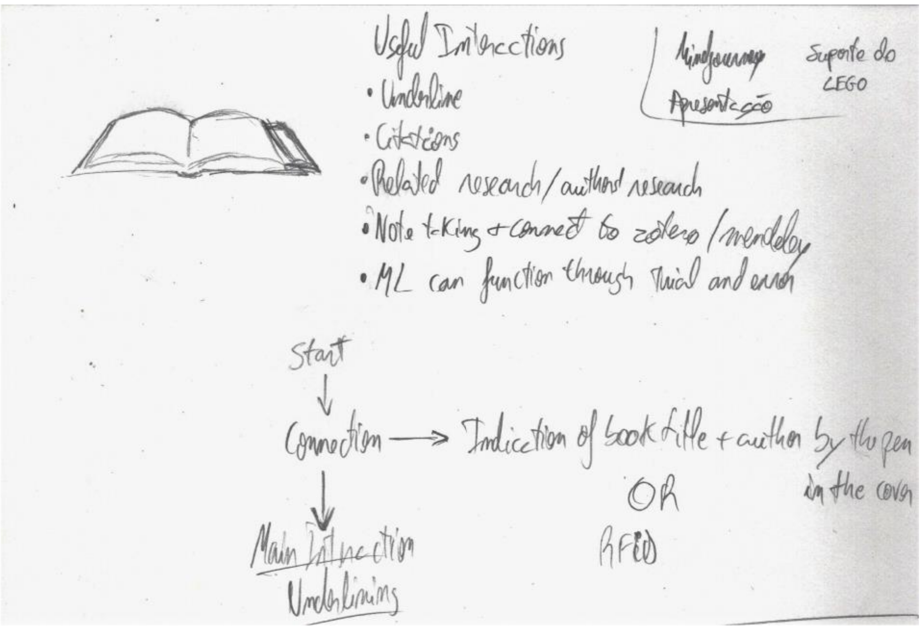


Fig. 56 – Sketches for the Tangible Research Assistant.

Following that process, we began producing interaction aspects that would occur, such as how the user would highlight textual information and how the interface would respond. The main concern in this phase was how could the device integrate autonomous systems and provide relevant outputs to user's research. With that in mind, as the objects of research that were the support for this proposal would be usually registered in scientific databases, with a digital copy of the document, AI would be able to access the same information available to the user. With this in mind, the integrated computational components would allow for an interaction that connected a physical copy of a document and all the related research, be it by being specifically mentioned in the book or by similar keywords, for example. This opened up possibilities in which the interface could be influential, as it would broaden the quantity of research that would be available to the user, promoting a more beneficial aspect of reading in a print media. Then, the device started taking shape, as it was inspired by commonly used artifacts that accompany the reading experience, such as a pen or a pencil, and a tab that could be coupled with any book. These two options were the defining aspects of how the design proposal came to fruition, and the coupling of a pen that would be the input device and a digital tab that would be responsible for the output were the two components that integrated the system (Fig. 57).

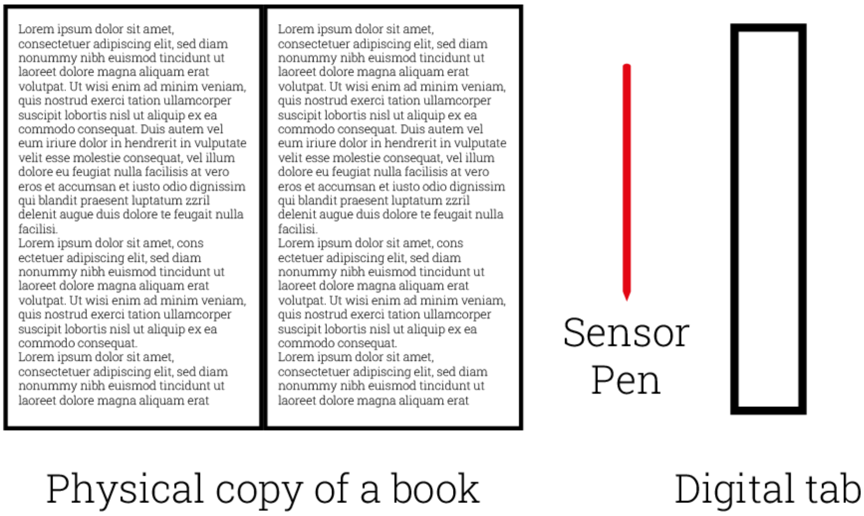


Fig. 57 – Components of the Tangible Research Assistant.

The device would not affect the integrity of the book, so the choice for a sensor pen would be the alternative to it, as it could still provide information about highlighted text, but through a harmless action. The sensor-imbued pen would register the location of the pen in relation to the line of text that would be selected, by underlining it while holding an input button, and then transfer that text segment into the device's database system. The digital tab would be inserted in between the back cover of the book and the last page, as it could sensor the page in which the text highlighting was taking place. This could either be done by bend sensors that would recognize the number of pages that were turned or a weight sensor for the number of pages on top of the tab. Regardless of the technology that would be used to achieve the process of underlining and localizing the text segments that the user chose to. With the initial characterization of physical manifestations of the interface, the research output needed to be taken into account, as information displayed needed to be explored to better define the system. As the user would underline a specific segment in the book, the digital tab would acknowledge it and provide three sections of related information: related keywords, which would provide information as to the context in which the quote is integrated; related research, as the text segment could be related to a specific research topic that differs from the original concepts; and finally, a list of references that although not necessarily related to selected section can also be of help when producing a research document. With these propositions in mind, autonomous systems would have the biggest influence in this specific section of the interface, as they would provide information with tools that assess the relevance of research. The evaluation of relevancy could be done through time spent on specific papers when reading a particular book, providing the ML system with an iterative database that is constantly updated as more researchers interact and with the research assistant. Finally, the proposal also took into account that any annotations, citations and related research of each reading session could be collected and paired with a digital software that would list the accessed documents, so that users can keep their bibliographies organized and accessible. The whole interaction process is mapped in Figure 58.

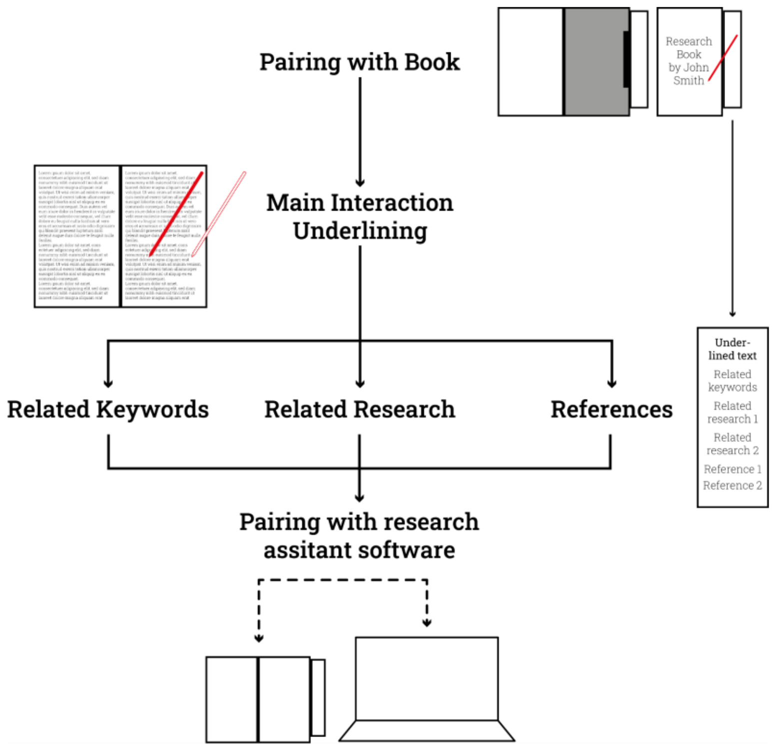


Fig. 58 – Interaction steps of the Tangible Research Assistant.

As the proposal stands, the main improvement that would follow would be the visual definition of textual aspects to be displayed in the digital tab, as the potential of the interface relies on the execution of that component.

6. E-ink Updatable Poster

Acknowledging the properties of recent e-ink displays, as an accessible, efficient and versatile alternative to common digital displays, this proposal seeks to experiment with the benefits of having an electronic paper sheet in public areas. Taking into account the reflectivity that e-paper technology possesses, its application in an outside setting could prove to be the bridge between typical printed posters and dynamic digital displays. The chosen context for application of this proposal was the culture and arts as the promotion of those fields is usually made through static printed media. This would help to not only dynamize the static information present in those supports, but to also better utilize the visual expression of such events. Therefore, this proposal sought to improve the overall experience of interacting with posters, through a dynamic and smart interface that would change depending on user's behavior. With that starting point, we began representing different actions that would prompt the poster to provide feedback. Imagining that a poster is on a wall within a public space, if a user is walking by, the system would acknowledge and react, attempting to draw attention to the poster. As the user moves closer to the poster, it dynamically changes information depending on where the user is directing attention, through eye tracking and movement sensors, integrated with autonomous systems. Depending on the user's time of exploring the poster's information, it would react by expanding on specific details the user might be looking interested in, and could also present another content, related to the original poster image. Finally, as the user walked away from the display, the poster would go back to the initial configuration, waiting for the next interaction to take place (Fig. 59)

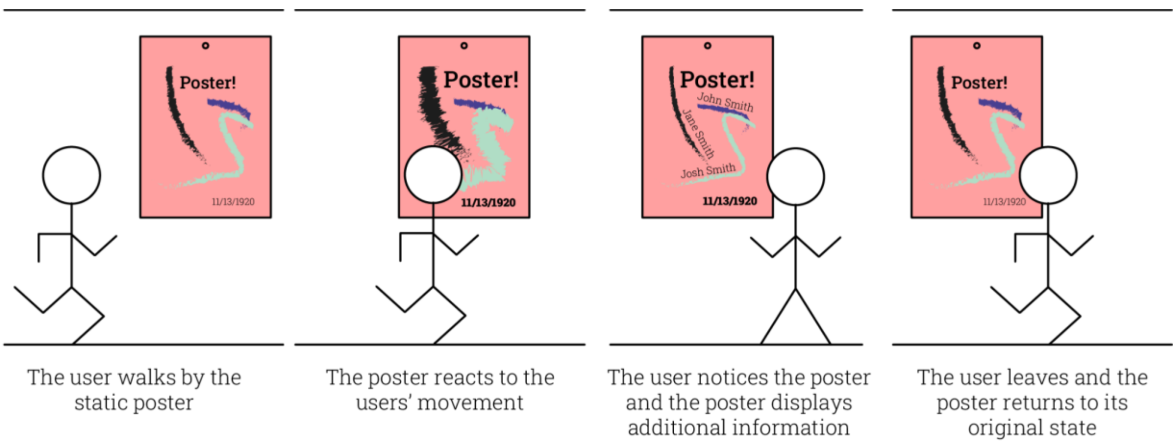


Fig. 59 – Simulated Interaction for the E-ink Updatable Poster.

Additionally, the system would evaluate, through AI and ML tools, the success of each poster, depending on time spent by users for each event that was being promoted, allowing for an adaptability that would result in more attention being brought to the poster. As well as assessing which content would be more interesting for a specific area or context, the integration could also provide insights as to improve the visual expressions inherent to each poster. Although this might hinder graphic design's production, as it is bringing constraints for its identity, the dynamization of a display can also be a favorable tool to work around those. Other variations of the poster reactions were explored in Figure 60.

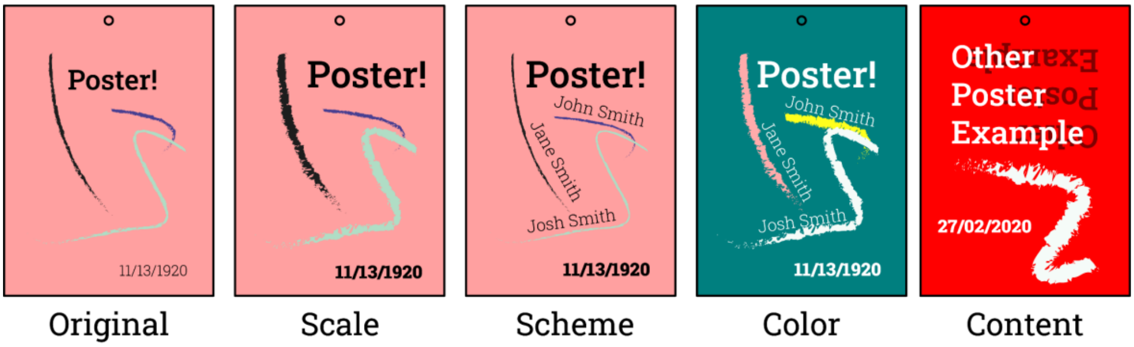
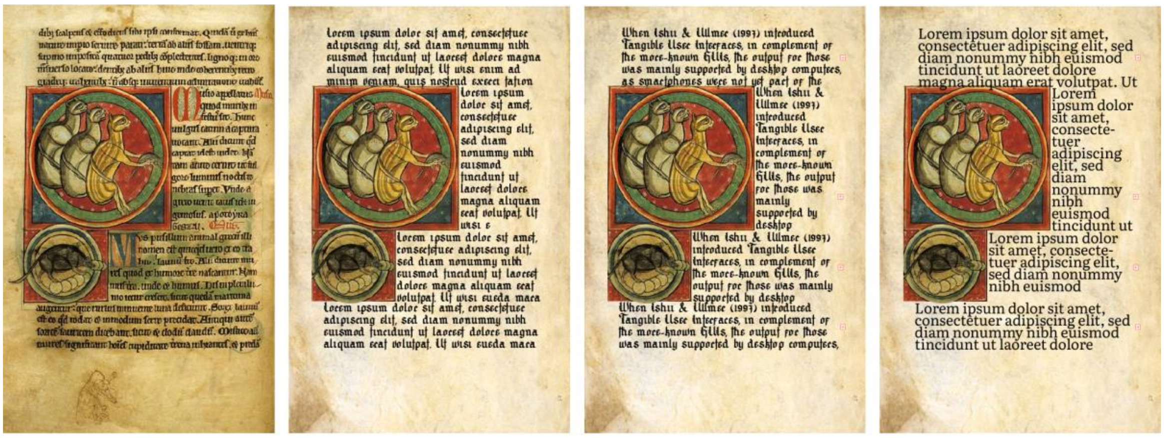


Fig. 60 – Additional visual variations for the E-ink Updatable Poster.

As this proposal does not possess the same kind of materiality as previous ones, the added dynamic aspect of the poster overcomes the need for it, as the added dimension of time is evident throughout the whole interaction process.

7. Historical Literature Smart Translator

For the last proposal, we looked into approaching the historical literature material as an opportunity to value the unique visual and literary expressions inherent to some of the most known printed objects. As these artifacts are usually very rare and not easily accessible, producing a device that allows for the manipulation of them without putting their integrity at risk would be the main two purposes. Another detail to be taken into account is the translation, given that some of the texts would not be originally written in contemporary languages, its comprehension would be interfered by that. As these texts are so expressive and particular in their visual identity, be it by hand drawn imagery, or an unique font that does not have a digital counterpart, one of the challenges of this device would be to maintain those aesthetic aspects, while still providing a more accessible support. The device would be composed mostly of a flexible e-paper display to mimic the manipulation of a physical book, while having a dynamic interactivity purpose. Using bend and touch sensors, the users can use the display as a typical book for turning pages. The main aspect of the system would not be its interactivity per se, but the possibilities of integrating this interface with autonomous systems. As AI and ML are gradually being introduced in artistic creation and language interpretation contexts, the opportunities have arisen to apply these two approaches in this proposal. Given the linguistic nature characteristic to these documents, a trial-and-error process might occur to better translate them through autonomous systems, but ML algorithms have taken strides to increase the effectiveness of that process. As that aspect had been thought of, the main unpredictability would be the configuration of the artistic styles regarding each text, as it would require a complex process to achieve correctly. As it is hoped that those possibilities are eventually achieved through technological advances, we did not delve in its intricacies. With the definition of the influence of autonomous systems on the device, the main contexts in which it could be applied were seen as libraries, which would help the access to the documents; museums as the places in which some texts are presented to the public but are seen at a distance; and research laboratories, as the translation of both the text and the visual aspects can prompt insights into the historical and cultural aspects of the produced content. The following characteristics that were reflected on would be the possible options for interaction. The focus of this interface would be to produce translated versions of original literature documents, therefore, we planned for three variations to be explored in the interface. Firstly, the device would present the original content, so that users of different levels of interest would acknowledge the starting point of the interaction; secondly, the booklet would translate the text to the selected language by the user, through AI and ML; then, as the letter types that were used might not be the easiest to read, a shift to a more accessible font is also available, maintaining the configuration of the pages and the translated text, as shown in Figure 61.



Original copy | Digital version | Text translated | Changed font for better reading

Fig. 61 – Variations of the Historical Literature Smart Translator.

As this proposal is with the least focus on materiality and interaction, we would seek to develop those aspects of the device, given that it is still in a very early concept phase.

End Note

Following the theoretical, conceptual and material insights produced in the first three chapters of this document, the whole materialization of possible manifestations was described in this chapter. With a concern with the methodology of RtD, we sought to comprehend the concepts that follow this process. This resulted in a thorough assessment of various perspectives that exist in the scientific community regarding research and design as complementary subjects. One of the main takeaways was the lack of research done on this method, as several authors pointed to the gap between practice and theory of producing interaction design. This is especially relevant given that each researcher attempted to produce arguments to bring the RtD concept into a specific scope. Regardless of the different approaches in different documents, the final goal of producing research insights was the main concern. This allowed us to not be hindered by a specific approach, but to acknowledge each one and through a complementary process we produced a concise and concrete methodology. The addition of compositional material interaction design was also crucial as it allowed the approach to be part of the bigger scope of this research, and every concept was brought together into the structure. With the methodology finally defined, the following section was characterized by the production of design proposals and its description through an iterative process of RtD. The concern on materiality and tangibility was evident in most of the ideation as the focus on these concepts is maintained throughout the whole document. We presented clear visions as how to move forward in each of the proposals, as the production of possible prototypes was not the focus of this research. Obtained results in this chapter are relevant to the main research goal, which is the identification of possible interactions in AI-enhanced interactive print in a RtD methodology. The quantity of design proposals and the proposed method focused on material-centered interaction is a prevalent argument that there is still much to be done in this context, particularly from an interaction design theory scope.

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Conclusions

Interaction design is in transition, researchers are concerned with the expressions and challenges of the third wave of HCI and how it will shape the field in coming years. In sight of this, there is a tendency that does not seek to dematerialize interfaces into invisible devices, but to better use future technologies to provide shape, meaning and form to interaction. To understand and visualize the current state of the concepts that are prevalent in the field, we produced a cognitive map to address this. The present context of interaction design is characterized by its expansiveness and versatility of possibilities inherent to the field. This is a stimulating finding given the premise and opportunities available to interaction designers to approach specific contexts with particular tools. Despite this, the research paradigm of theories such as tangible interaction and interactive print have become stale, particularly when comparing with the emergence of practice in Ubiquitous Computing, IoT and Autonomous Systems. Additionally, traditional interaction materials were being overlooked as relevant to the future of interaction design, without acknowledging its full capabilities with contemporary approaches. This is the case for printed media, since hyperlink media innovation has severely lacked enhancement in its manifestation, denoted as the '"death of print'. This was consistent throughout the production of the literature review as the references for print media and autonomous systems in an interaction-focused approach were scarce. Furthermore, it has had very little involvement with interactive systems, specially approaches that are flexible and adaptable, with capabilities to integrate and augment strictly static devices, such as autonomous systems. This context prompted the development of a research through design process, as there is a considerable gap in the Interaction Design community regarding interactive print media, especially when paired with AI. Therefore, the production of a RtD methodology based on the literature review made on this subject allowed for a versatile and dynamic methodology for the development of design proposals based on the premise of AI-enhanced interactive print media. This was accomplished by a material-centered compositional approach, with sketching as the main tool for the visualization of possible manifestations, as iterative design remained at the forefront of ideations.

A. Discussion of Research Goals

The first main goal (G1) of this research resided in the contextualization of research topics that were inherent to interaction design, in order to find connections, tendencies and complementary natures of each. This goal was also segmented into two distinct objectives, G1.1. and G1.2., which are correspondent to the first three chapters of this document. The acknowledgement of the three waves of HCI as the guide for the evolution of the field since its inception allows researchers to follow a train of thought that justifies and unifies the context that we addressed. Production of the cognitive map and the following definition of concepts that composed the context in which this document would provide relevant insights as a first step of the research. Separation of the three groups of concepts in the cognitive mapping allowed for a comparison between the resulting research and practice tendencies of each of them. For example, although AR and AI systems are steadily evolving and providing technological innovations, the print media section has been overlooked in the Interaction Design context ever since hyperlink media was introduced. Additionally, the discrepancy of quantity components that are related to the second and third wave of HCI is relevant to acknowledge the lack of interest in this field. The relevancy of the map is not just in its final output, but its process proved to be stimulating, as the research in which it was based was multidisciplinary, which allowed for a complete and balanced approach. The following section of the first chapter was the definition of one of the main concepts that would be focal to the whole process of the dissertation: the materiality of interaction. Providing a thorough exposition of the concerns of several researchers regarding a material-centered approach to interaction design made it so that there was a guiding thought throughout the full development of the research.

In the second chapter, the focus was on tangible interaction, as we believe that approach will foster the concepts of materiality, and provide researchers with tools to create multimodal and versatile interfaces. The definition of existing lines of thought in this field is not new, as researchers have been concerned with the congregation of concepts inherent to TUI for more than a decade. Although this is the case, most of the recent research produced in this context, have had fairly distinct approaches and concepts in focus. This prompted us to reassess the conceptual frameworks of tangible interaction in an attempt to unify them, providing future researchers with a complete groundwork for TUI development. The main takeaway of this process was the analysis of each framework which specified the characteristics of conceptual structures, allowing for a thorough understanding of each one. Following that, we acknowledged a lack of a scheme that attempted to incorporate each approach in a concise structure, from the multimodal interface by Ishii, or the concern with feedforward by Wensveen, for example. Additionally, as this research has a material-centered interaction approach, one of the goals for this chapter was to incorporate materiality in a TUI framework, as a way to provide future tendencies with a stable groundwork. With the conclusion of this chapter, we acknowledge the achievement of the contextualization and exposition of concepts and their role in this document were defined, as well as the connections between each of them.

The third chapter of this thesis refers to the partial concretization of the two main research goals, as the AI-enhanced interactive print is the theme to be approached in a research through design approach. Not only that but acknowledging the present state of both print media and autonomous systems in an interaction design context is also insightful for this document. The purpose of this section was to also recognize print media as an interaction design material, as it remains very accessible, versatile with a promising potential for stimulation manipulation. One of the main takeaways of this was the lack of research that has been produced in this context, as authors consider that print media is not part of future interaction design tendencies. Additionally, this chapter also tackled autonomous systems as tools for interaction design, and the quantity of research done from an HCI approach was underwhelming, resulting in an unexpectedly smaller output in this document. This was also the case for interactive print media, reinforcing the value and relevance of this research, as both of these concepts can still produce stimulating interactions for the future of the field. This made for an additional goal of this dissertation, as we hope that designers and researchers alike can be prompted to approach this concern and promote the exploration of interfaces with this in mind. The conclusion of this chapter provides designers with the description of the possibilities for each of the materials for interaction design, and it fueled the following chapter's RtD development.

The fourth chapter was dedicated to the completion of the second main research goal in mind, relating to the production of a research through design approach for AI-enhanced interactive print. Taking into account the context and materials, the first step was the production of the methodology that would guide the development of the RtD. In a process that was based on the materiality of interaction approach, while still encompassing the concepts of tangible interaction and centered around print media and autonomous systems. Although it could have posed as a challenging task, the values of each approach fit in naturally and therefore provided a complete groundwork for the production of the methodology. Through sketching and brainstorming, the structure that would be followed in this phase had several iterations, resulting in a concrete but adaptable scheme. This approach had an additional goal which was to provide designers and researchers with guidelines to introduce the materials and interactions that were available or chosen to them, allowing for a future iteration of the proposed model. This means that although the structure that is presented in this document is relevant to the scientific community, it is not a final iteration, as we hope that others can improve and adapt it to other variables. With the conclusion of the RtD methodology, the following step was dedicated to the definition of design proposals that verified the hypothesis of this research. As the process went along, the quantity of possible manifestations of AI-enhanced interactive print devices proved that there is still potential for both research and practice in this field. This also confirmed the second main goal of this dissertation, as a research through design process was carried out with considerable results. Additionally, the iterations of each design proposal also provided relevant insights into the development of the devices, given the context and methodology. The first iterations had manifestations similar to the sketches that preceded them, meaning that these were mostly bidimensional devices, with a focus on defining the concepts that would be central to each proposal. Then, the second iterations were characterized by its added materiality, as the visual expression started to rise, with mechanical and computational features becoming gradually more robust. Finally, the last iterations of the proposals were focused on the integration of AI and ML in the devices, as they allowed for an additional layer to be added, mainly through personalized interactions.

With the conclusion of the process, we believe that each goal was achieved with success, as the insights in the present context of research in the interaction design can prove relevant for years to come. This is also true for concepts such as interactive print media, material and tangible interaction, as these have lacked relevant studies that sought to connect and relate each one. The contextualization can also prove to be relevant to future Interaction Design tendencies, as we believe that there are still potential stimulating opportunities to develop material-centered interaction design proposals.

B. Limitations of this thesis

As has been acknowledged briefly throughout the chapters of this dissertation, the lack of research hindered the production of the literature review and contextualization of various topics that were inherent to this research. Mainly in the interactive print field, the research that was reviewed had an underwhelmingly light quantity of documents that promoted the production of research on this subject. Additionally, the few authors that were concerned with this situation produced most of the references that were assessed in this dissertation, meaning that even the number of documents that were referenced were produced by a small number of researchers. This was also true for autonomous systems, when in relation to interaction design practice, the references were very limited, as there was an absence of concern regarding the future of AI and ML in interaction design. This hindered the thorough comprehension of the tools that autonomous systems can provide in an interactive print approach, as both those topics lacked considerable research. Regarding the research through design process, the goal was to produce a guideline for production in AI-enhanced interactive print, so the final outcome would not be dependent on the quality of the design proposals. As addressed previously, the methodology was produced to allow for a large quantity of design proposals so the seven examples that were described in this thesis have the potential to be much more. This was also true for the state in which the ideation was halted, as there was no prototyping in the developing process. This was due to the time it would have taken to produce such semi-functional prototypes, as we believe that this document had to be balanced in the theoretical-practical components. Additionally, the prototyping process would have required a budget for acquiring computational materials and that was not considered to be crucial for the development of this research.

C. Future Studies

Although we believe that the research goals of this dissertation were achieved, there would still be processes in which we would improve and build on, given the bases that were produced. One of the objectives to accomplish following the conclusion of this document would be to subject the proposed M-TUI model to an evaluation process by researchers that are specialized in this approach. To better assess the capabilities of the framework, dissemination would be crucial for this to come to fruition, as we believe that there is potential for the framework to be insightful for future research. Additionally, refinement and appraisal of the methodology for research through design would also be a topic to be addressed as we understand that different variables can be introduced in the proposed scheme. As there could have been stimulating inputs from other researchers and designers, the structure of the model could have been adapted to fit other contexts. Furthermore, we believe that applying the methodology to a co-design development process would also benefit future ideations of the system, and for the quantity of design proposals that result from this method. Finally, to wrap up the process of research through design, we would attempt to finish the prototyping of high-fidelity and functional devices that have come from the design proposals.

D. Dissemination

This research, was carried out within the “<DIV> design, interaction and visualization” research group, and information was published in the respective website: https://div.fa.ulisboa.pt/

Additionally, the research also counted with a website that shared contributions from this document: https://increase.fa.ulisboa.pt/

In September of 2022, a presentation to students of the second year of the master’s degree in Interaction Design at the Lisbon School of Architecture was made with the goal of exemplifying the research through design approach.

Finally, a paper regarding the production of the cognitive map entitled as “Cognitive Mapping for AI-augmented Interactive Print” has been accepted for presentation and publication at HCI International 2023.

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