8-2019

Toward New Ecologies of Cyberphysical Representational Forms, Scales, and Modalities

Alexandre Gomes de Siqueira
Clemson University, alexandre.g.siqueira@gmail.com

Toward new ecologies of cyberphysical representational forms, scales, and modalities

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Human-centered Computing

by
Alexandre Gomes de Siqueira
August 2019

Accepted by:
Dr. Brygg Ullmer, Committee Chair
Dr. Larry F. Hodges
Dr. Sabarish Babu
Dr. Andrew Robb

Abstract

Research on tangible user interfaces commonly focuses on tangible interfaces acting alone or in comparison with screen-based multi-touch or graphical interfaces. In contrast, hybrid approaches can be seen as the norm for established "mainstream" interaction paradigms. This dissertation describes interfaces that support complementary information mediations, representational forms, and scales toward an ecology of systems embodying hybrid interaction modalities. I investigate systems combining tangible and multi-touch, as well as systems combining tangible and virtual reality interaction. For each of them, I describe work focusing on design and fabrication aspects, as well as work focusing on reproducibility, engagement, legibility, and perception aspects.

Dedication

To my wife

Bruna - Because of your continued support and unconditional love. You inspired and encouraged me every step of the way.

To my Mom and Dad

Mrs. Maria A. G. de Siqueira and Mr. Jairson L. de Siqueira - For making me who I am today.

To my in-laws

Mrs. Eunice de M. Navarro and Mr. Gilberto N. Modesto - for their love, support and encouragement.

Acknowledgments

The authors wish to gratefully acknowledge that this research was partially supported by the Coordination for the Improvement of Higher Education Personnel (CAPES) through the Science without Borders scholarship program from Brazil, with additional support from Louisiana State University, Center for Computation and Technology (CCT), Clemson University, NSF CNS-1126739 and NSF CNS-1828611.

First of all, I wish to express my deepest gratitude to Dr. Brygg Ullmer for his consistent support even before the start of my PhD. He believed in me and gave me the opportunity to blossom. He never deprived me of his time and advice even during his tightest schedules. He challenged and motivated me to think in unconventional ways, expanding possibilities and maximizing opportunities way beyond the boundaries of the Ph.D. program.

I have also had the pleasure of working with Dr. Chris Branton who guided and supported me for countless hours, throughout the early days of my Ph.D. program, and remains a constant reference and mentor.

I would like to also acknowledge Dr. Sabarish Babu for his time, dedication, guidance, and encouragement, which kept me motivated in overcoming several research obstacles. Furthermore, I would like to take the opportunity to appreciate invaluable suggestions and guidance that I received from Dr. Christopher Pagano and Dr. Andrew Robb during the last few years, which greatly benefited my experiments. I would also like to acknowledge Dr. Larry Hodges for welcoming me to the Clemson HCC Ph.D. program, his mentorship, and kind words whenever I sought his advice.

I would also like to acknowledge Dr. Konkel, for her support and decisive words when I needed them, and Dr. Nathan Mcneese for sharing his knowledge and support during the Ph.D. program. I would like to thank the support of Drs. Karki, Costas, Carver, Berdahl, Wischusen, Carmichael, Moreno, Butler, and Allison from Louisiana State University who provided me with invaluable insight and opportunities. I would like to thank the undergraduate students Mark DeLarosa, Eli Berkowitz, Grey Patterson, Dwayne Hinton, Bianca Hilderbrad, Sarah Thompson, Tracy Nguyen and Logan Bartell for their work and dedication developing the digital poster prototypes discussed in this dissertation. I would also like to acknowledge Ayush Bahrgava, who spent so many hours discussing, developing, and co-authoring the tutorial on combining tangibles and virtual reality we presented across the ocean.

I would also like to thank fellow graduate students Mustafa Hajij, Shayan Shams, and Marija Zivanovic who shared their expertise, friendship, and free time with me and my wife during our time in Baton Rouge. I would also like to thank Ben Guitreau (in postumum), Jing Lyu and Moloud Nasiri for their time and support in so many projects related to this dissertation. I would also like to thank undergraduate students Wajdi Halabi, and Carson Wood for all the help, support, and fun times. And a special thanks to Leandro Gazineo, Carmem Gazineo, Luciano Correa and Suelen Corleone who lightened my days with their friendship and warmth.

I owe a debt of gratitude to my wife who have always earnestly devoted her moral support and time in my hours of need. Last but not the least, I would like to acknowledge my family and friends who always supported and encouraged me whenever I needed them, and helped me to achieve my goal and complete my dissertation work successfully.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Screen-based graphics and text still remain the primary means for representing digital information. Screens, both big and small, in our desks, pockets, head-mounted, or embedded in the environment, usually in combination with general-purpose input devices, remain arguably the central element of most mainstream human-computer interaction paradigms.

While successful, one recognized limitation of graphical user interfaces (GUI) in general, and the "WIMP" (windows-icon-menu-pointer) in particular is the "input" and "output" asymmetry. Regarding this, Ullmer [263] asserts:

> *"While often employing millions of pixels of graphical output, WIMP interfaces generally rely upon a single locus of pointer-driven input, in a style largely devoid of physical and kinesthetic affordances, or other handles for engaging with a world of multiple users, each with two hands and a lifetime of physical skills."*

The last decades have seen a number of research efforts and commercially available systems exploring ways to overcome these limitations and better link the physical and digital worlds. These efforts have inspired several research areas such as virtual and augmented reality, ubiquitous computing, wearable computing, research on tangible user interfaces (TUI), and driven the popularization of interaction paradigms such as voice and gesture.

While tangible interfaces offer interaction beyond the trio screen-mouse-keyboard, within the tangible interaction field research often focuses on tangible interfaces acting by themselves or tangible interfaces in comparison with "competing" interaction techniques (e.g. graphical and multi-touch interfaces [295, 83]). In contrast, when considering established "mainstream" interaction paradigms (e.g. GUIs), hybrid approaches can be seen as more the norm than the exception.

Reflecting upon the Xerox Star system, its creators warned not to be dogmatic about direct manipulation on Desktop metaphor [153]. Contemporary operating systems and desktop computer applications tend to combine both graphical user interfaces and textual/command-line interfaces. Operating systems, in particular smart-phone platforms, typically blend multi-touch within more "traditional" applications (e.g., web browsers). Voice activated devices, such as Amazon Echo [218], often come in a range of sizes, and do not rely solely on audio input/output, instead combining primary voice-activated interaction with buttons for input, and sound and (LED) illumination for output.

These combinations of input and output modalities, along with combinations of fabrication approaches, materials, forms, and scales, may be key to circumventing issues and limitations of individual interaction approaches. In this dissertation, I develop and explore several systems combining a number of cyberphysical representational forms, scales, and interaction modalities which are presented and analysed regarding fabrication approaches, reproducibility, legibility, and perceptual aspects. After clarifying a working interpretation of these terms, I demonstrate that hybrids of complimentary mediation modalities – including passive and dynamic, physical and virtual, and combinations thereof – can be more legible and actionable than when they are considered alone.

1.0.1 Ecologies of Representational Forms, Scales, and Modalities

In 1991 Mark Weiser published the seminal paper, "The Computer for the 21st Century [278]". He envisioned devices of three scales: tabs, pads, and boards. Tabs are inch-scale devices, which he envisioned as active Post-it notes; Pads are foot-scale devices, the size of a sheet of paper, a book, or magazine; Boards are defined as yard-scale devices, with size equivalent to blackboards. While each envisioned device can be considered independently, Weiser describes them as complementing each other, and forming an interconnected system, through which information and interaction flows. It is notable that these devices are not just "interconnected" by sharing the same "network", they are interconnected by complementing interaction paradigms, forms, and scales; something that is even today not common.

In 2014, Bill Buxton [63] (then serving as Principal Researcher at Microsoft) proposed going beyond the focus on individual systems and devices, and looking at them from an *ecological* perspective. *Ecology* is the branch of science concerned with the interrelationship of organisms (in this context, devices) and their environments [8]. I find this definition valuable to the work presented in this dissertation since several systems and devices created are aimed at complementing each other in their forms, scales, and interaction modalities, toward defining an "ecology" of devices.

While an arbitrary number of diverse structures, forms, and scales could be realized, from a research-oriented point of view, evolving systems and physical devices which share (some or most) characteristics allows us to more effectively compare, contrast, and aspire to generalize properties among them. Several of the systems developed are therefore "isomorphic" in nature. Isomorphs can be defined as being of identical or similar form, shape, or structure [39]. One example of isomorph in this work is the application of both large (approx. 60 inches) horizontal and vertical multi-touch screens, as well as small (approx. 10-inch) tablets for display and interaction. Another example is shown in figure 1.1. The challenge coins, and challenge clocks, further discussed in later chapters, can be considered isomorphs in shape and mediation strategies, albeit varying in size, and purpose.

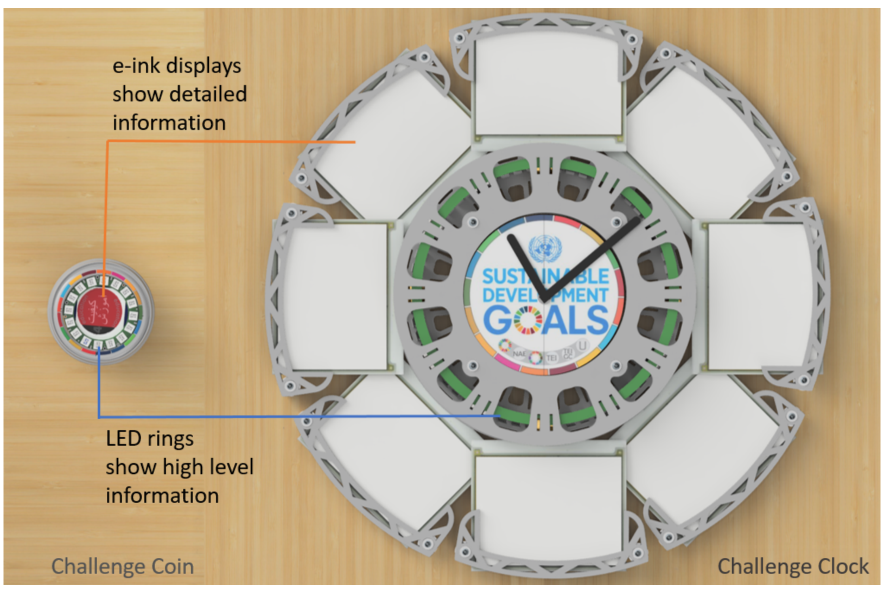


Figure 1.1: **Example of isomorphic artifacts: Challenge Coins and Challenge Clocks.** *Both artifacts are round in shape, and employ two mediation strategies to express information: e-ink displays and LED rings. However, they vary in size and have diverse purposes and affordances. [164]*

In my initial work, I investigate the class of tangibles that involves passive and active cylinders, wheels, dials, pucks, and knobs. I explore design, fabrication approaches, and combinations of diverse materials and mediation strategies toward creating dials that are reproducible, and capable of interacting with multiple systems. Following this work, I explore engagement and usability aspects of a computationally mediated scientific poster platform that combines tangible and multi-touch interaction (with dials) into a single experience, with neither being considered intrinsically superior to the other. Than, I explore the design and fabrication of passive and active reproducible tangibles to be used within virtual reality (VR) environments, including immersive and non-immersive VR simulations. This is followed by an empirical evaluation of the effects of calibration on the near-field size perception of tangibles in immersive virtual environments (IVEs). Finally, I explore other forms, scales, and mediation strategies for tangible systems – beyond tangible dials – that embody several of the approaches and strategies discussed throughout this dissertation.

1.0.2 Design Heuristics and Approach

The systems I research engage multiple computationally-mediated interaction modalities, including touching something, moving something, rotating something, and beyond. Typical challenges of computationally-mediated systems relate to how one can tell what, how, and when to *do* something, especially when first exposed to a system. One common term associated with these challenges is Donald Norman's "affordance" [114]: perceived properties (that may not actually exist), which may provide suggestions or clues as to how, or when to use such properties. As illustrated by Donald Norman's work, even a single affordance may pose a design challenge (e.g. representing the affordance of opening of a door is a classic example [114].) This issue becomes even more complex as forms, scales, interaction, and information mediation modalities are combined.

Partly in response to such design challenge, I co-authored with Dr. Ullmer and others the LAVA heuristics [261]. The LAVA heuristics – **L**egible, **A**ctionable, **V**eritable, and **A**spirational – provide a conceptual tool for regarding representational and control aspects of interaction design in general, and tangible interfaces in particular.

- **legible:** Legibility can be defined as how devices are expressed in physical and visual representational forms so that they allow users and systems to "see" them, and "read" them. By "read" I mean that users (and systems) can perceive what artifacts represent. I will regard legibility as textual, form, and Lynchian:

Textual legibility: A direct approach to textual legibility is related to how text is used, and presented to users. Is the size, thickness, and overall shape of letters readable by users from an expected distance, position, or light condition? Is the text aimed at presenting detailed or high-level information? Long texts or short ones? All these questions support and guide the choice and use of text within tangible systems – and hybrid ones. As an example, in section 5.5.1, I present a system combining immersive and non-immersive VR interaction that shows long texts on large LCD displays, while displaying only short texts within an immersive virtual reality environment. While the long texts are not comfortable to read in immersed VR (considering current HMD technology), they can be comfortably read when displayed by the large LCD displays.

Form legibility: Form is another important factor for legibility. Instead of considering form as how it communicates functionality (I will discuss that under actionability), form legibility is concerned with what a given form may represent, beyond function. Here, cultural prospects may play important roles. It may be widely recognizable that the hammer and sickle arranged in a particular way may be associated with communism; a white five-point star over a red background is associated with a particular political party in Brazil.

Lynchian legibility: The perspective of "legibility" also draws from Kevin Lynch's seminal urban planning text "Image of the City" [164]. There, he studied how several critical anatomical features of cities (Figure 1.2) shaped both the physical structure of cities and peoples mental maps of these spaces. He argued that how these compositional elements were spatially employed (often over the course of centuries) had substantial impact on their legibility, as well as people's perceptions:

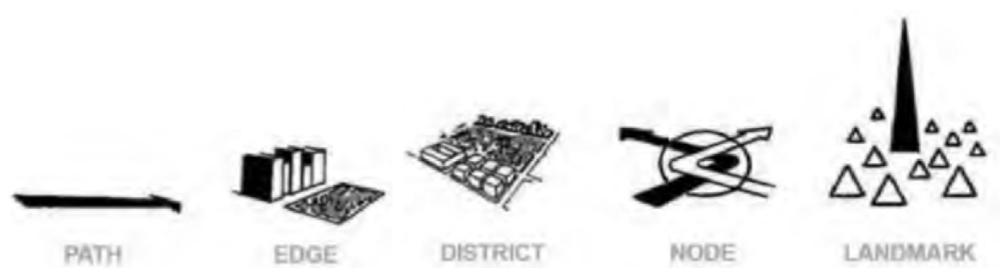


Figure 1.2: **Image of the City:** *Lynch's illustrations of path, edge, district, node, and landmark patterns within urban spaces. [164]*

mediation modality	passive	dynamic
visual	2D print	screen or projective
shape	3D print	actuated 3D form
material	traditional material	actuatable material (electroluminescent, dynamiccolor, etc.)
performative	fixed position	moving, dancing

Table 1.1: **Complimentary forms of mediation.**

> "Just as this printed page, if it is legible, can be visually grasped as a related pattern of recognizable symbols, so a legible city would be one whose districts or landmarks or pathways are easily identifiable and are easily grouped into an over-all pattern.... Indeed, a distinctive and legible environment not only offers security but also heightens the potential depth and intensity of human experience." [164]

While somewhat differently framed than Lynch's patterns, in resonance with McLuhan's "the medium is the message" [192] the different technological and cognitive evocations of multiple forms of mediation – whether taken individually, or (perhaps especially) in combination – hold Lynchian analogues. These include a range of complementary mediations, briefly summarized in tabular form within Table 1.1.

Of the several TEI analogues to Lynch's patterns, I anticipate that hybrids of one or multiple of the above – complemented by physical, virtual, or cognitive aspects – could be more legible than any taken alone.

- **actionable:** *do the physical artifacts provide paths to access and/or manipulate aspects of their cyberphysical associations?* Actionability is deeply related to the concept of "affordance". (e.g.) Cylindrical knobs *invite* rotation. Here, beyond rotation, one has to consider the entire set of expected affordances users are expected to perceive from the objects. Are they supposed to lift the objects? Does the presence, or communicated affordance facilitate or hint function?

- **veritable:** *do devices and their mediations provide means to ascertain the accuracy and "truthfulness" of represented content, and their readiness thereof?* The design should match its intended use and environment to be perceived as truthful. The look and feel of an artifact intended for the office may differ considerably from one designed for the classroom, or for the factory floor, affecting their veritability.

- **aspirational:** *do physical prototypes provide aesthetic motivation to engage, and suggest paths toward creating like forms?* Well-designed devices should motivate engagement and attract users with its aesthetic and functional qualities. They can motivate engagement (e.g.) by evoking emotions, and memories.

In this work, I analyze and discuss the design and interaction of an ecology of computationally-mediated systems that were developed in light of the LAVA heuristics. A number of the systems developed were taken to several venues both in and out of the US, with over a thousand users interacting with them. The LAVA heuristics is also explored in the "fullborn" fabrication and deployment framework, in Appendix F.

1.1 Thesis Statement

This dissertation works to support the following thesis:

Computationally-mediated systems consisting of hybrids of complimentary cyberphysical representational forms, scales, and mediation modalities can demonstrate enhanced legibility and actionability in comparison to non-hybrid ones.

The systems proposed by this dissertation often offer functionality *with* and *without* tangibles, and *with* and *without* virtual/"soft" interactors, including combinations of both. I regard (e.g.) "pure-multitouch" and "pure-tangible" variants, big or small, with active and passive artifacts, as well as hybrids thereof, all as "first class citizens". In this sense, the proposed systems are often not strictly a "tangible interface" system alone, but rather (inspired by [171, 173, 169]) what I and others have begun to consider as *cyberphysical interfaces* – systems designed to integrate support for multiple physical and virtual interaction.

1.2 Thesis Contribution

In supporting the thesis statement, the dissertation makes a number of specific contributions.

1. *Identification and characterization of hybrid representational forms, scales, and modalities as an approach toward enhanced legibility and actionability in cyberphysical systems.*

   The thesis is broadly concerned with the design and characterization of systems embodying hybrids of cyberphysical representational forms, scales, and modalities. This approach is supported both by systems designed toward the thesis, as well as other recent and previous work. However, the identification, expression, and characterization of these hybrids as capable of promoting enhanced legibility and actionability in cyberphysical systems is original to the work of this thesis.

2. *Realization and demonstration of a number of prototyped cyberphysical systems, which embody multiple complimentary representational forms, scales, and mediation modalities.*

   The thesis develops cyberphysical systems in a number of representational forms, scales and mediation modalities. I argue that such systems can demonstrate enhanced legibility and actionability in comparison to non-hybrid ones.

3. *Entrada Poster Platform*

   The Entrada Poster Platform realizes a platform for scientific poster presentations with a unique combination of tangible and multi-touch interaction, with large (approx. 55-inch) displays, and small-scale (tablet sized) variants, with and without physical interactors. This platform embodies several of the characteristics proposed by this work.

4. *Empirical evaluation of the effects of calibration on the near-field size perception of tangibles in immersive virtual environments*

   This thesis evaluates the effects of calibration on the near-field size perception of tangibles in immersive virtual reality environments of users interacting with tangibles of graspable sizes, such as knobs and dials.

5. *Proposal and realization of strategies to enhance the legibility of tangible artifacts based on low-count LED illumination and electronic paper displays for information mediation*

   This thesis demonstrates several strategies to enhance the legibility of tangible artifacts employing LED rings and e-ink displays to mediate information, both in the near and medium fields, in diverse scales and representational forms.

6. *Proposal and realization of a framework for fabricating and deploying cyberphysical systems geared toward out-of-the-lab encounters.*

   A number of the systems developed were exposed to users in conference demos, tutorials, live music presentations, and beyond. Several research efforts explore design and fabrication of prototypes geared toward commercial products, or are limited to the lab environment. The thesis proposes the fullborn framework for designing and fabricating cyberphysical systems geared toward environments beyond the lab. The detailed description of the fullborn framework is described in Appendix F.

1.3 Thesis Overview

The following chapter considers broad background and related work. The chapter begins by exploring tangible user interfaces in general, and knobs, tokens, wheels, and dials in particular. In this context, I explore a number of prior work on sensing approaches for tangible tracking. I explore work related to two of my own major project themes: computationally-mediated scientific posters, and virtual reality.

Chapter 3 presents a number of (combinations of) fabrication and sensing approaches for creating tangible knobs of several forms, shapes, and materials, which may be active, passive, hybrids, or combinations thereof, later applied to a number of projects, including several presented in this dissertation. Chapter 4 explores aspects of engagement and usability in systems combining tangible and multi-touch interaction.

Chapter 5 explores design and fabrication approaches of tangibles for virtual reality for both immersive and non-immersive simulations, and chapter 6 describes an empirical evaluation of the effects of calibration on the near-field size perception of tangibles in immersive virtual reality environments.

Chapter 7 describes additional representational forms, scales, and interaction modalities for devices beyond tangible dials, such as Challenge Clocks and tangible discs. Finally, Chapter 8 explores the conclusions and discusses future prospects of the approaches proposed in this dissertation work.

Figure 1.3 summarizes the overall organization of this theses, with some chapters focusing on design and fabrication, others focusing on engagement, legibility, and perception for systems that sometimes combine tangible and multi-touch interaction, and sometimes combine tangibles and virtual reality.

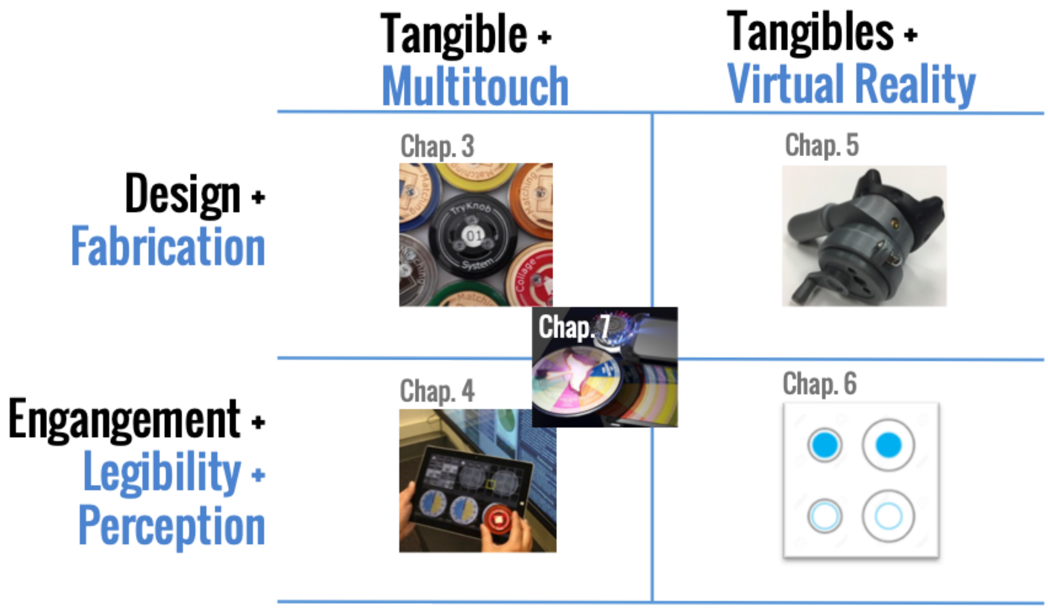


Figure 1.3: **Overview:** *This theses discusses interfaces combining tangible and multi-touch and tangible and VR interaction. Each hybrid interaction modality is analyzed both with focus on design and fabrication approaches, and with focus on engagement, legibility, or perception aspects. Chapter 7 further explores these hybrid interaction and mediation modalities analyzing variations on Active Challenge Coins, Challenge Clocks, and Tangible Discs.*

Chapter 2

Background and Related Work

Research beyond the WIMP (Windows-Icons-Menus-Pointer) paradigm has been an active topic in human-computer interaction, and has inspired a number of research areas. For example, ubiquitous computing [277] brings the notion of digital information and devices that inter-operate, with information seamlessly flowing among users and devices. Tangible augmented and virtual reality [161, 188, 136] combine tangible interaction approaches with augmented and virtual reality paradigms. These ideas have also inspired research on interaction with interfaces of growing physical scales, such as research on interactive surfaces and spaces, combining novel interaction techniques and emerging technologies, sometimes, involving room-sized interfaces, and beyond. In 1997, Ishii and Ullmer developed the Tangible Bits vision [150], emphasizing interaction both at the center and the periphery of attention, and inspiring research on other areas such as ambient displays, and peripheral interaction [86].

In this chapter, I begin by surveying these research areas, with a focus on how they aspire for broadly combining the digital and physical worlds. I give special attention to Tangible User Interfaces (TUI)s, in particular to the class of tangibles populated by cylindrical artifacts, sometimes called knobs, tokens, wheels, or dials. This is followed by background and related work on two other main topics discussed in this dissertation: scientific posters and virtual reality.

2.1 Broader Research Context

2.1.1 Ubiquitous Computing

Mark Weiser, then the director of the Computer Science Laboratory (CSL) at Xerox PARC, articulated his vision of ubiquitous computing in the seminal paper "The Computer for the 21 st Century" [277], published in Scientic American in 1991. Weiser envisioned a future in which interconnected computational devices are integrated seamlessly into our everyday lives. He promotes the notion of technology disappearing into the background, allowing people to focus on their tasks and activities rather than on operating devices. More interesting to this dissertation is his conceptualization of devices of diverse scales. For example, foot-scale pads, and yard-scale boards could support both individual and collaborative work. The former for individual use at an arm's length distance. The latter, for use by groups, inside a room. This has parallels to the computationally-mediated poster platform described in chapter 4, with tablets and large displays used in similar fashion as Weiser's pads and boards. In another parallel, the Active Challenge Coins described in chapter 3 share similarities with the inch-scale tabs described in Weiser's paper as dynamic information displays, or (e.g.) digital post-it notes. Weiser also envisioned tabs as trackers of location, activity, and objects. Research related, such as Sifteo Cubes [194], and commercially available smart buttons, activity trackers, and smart watches are other examples that embody characteristics of the tabs envisioned by Mark Weiser, and demonstrate its deep conceptual impacts.

Also related to ubiquitous computing is the notion of the Internet of Things (IoT) [38] – a network of connected devices with services for a wide range of application domains including smart homes, automotives, and cities. One distinction is that while IoT focuses on the development of new connected devices, data collection and analysis, the research of ubiquitous computing emphasizes human-computer and human-human interactions within a connected environment. Others have begun to blurry this line by (e.g.) in research which combines IoT and tangible interaction, in what is called the Internet of Tangible Things (IoTT) [80, 82].

2.1.2 Tangible Augmented and Virtual Reality

The goal of Augmented Reality (AR), similarly to ubiquitous computing, is to integrate digital information into the physical environment [195]. However, instead of integrating computing devices into physical objects, AR presents digital information alongside physical objects in the real world [195], usually through mobile devices or head-mounted displays.

In resonance with this dissertation, one of the goals of Tangible Augmented Reality (Tangible AR) interfaces is to combine tangible input and AR output [161, 172, 283]. In these approaches, virtual representations are "attached" to physical objects, and allow interaction both with the physical and digital representations. Wellner's Digital Desk [281] is an early example. A projection onto paper objects on a physical desk digitally augmented them, with computer vision technology tracking the location of the physical objects, as well as providing interaction with a pen and fingers.

Later projects display 3D-visualizations of virtual objects overlaid onto physical objects. Implementation ranges from tracking visual markers, to tracking the 3D objects in real-time. A number of academic examples can be found such as books [93], entertainment [300], and hybrid work environments [134]. However, virtual objects are easily distinguished from their physical counterparts upon touch due to the lack of haptic feedback [265], which can cause a visuo-haptic mismatch. When tracking 3D objects, recent work explores reducing this mismatch by scanning and selecting physical objects from the real environment that are similar to the virtual objects. Current research focuses on improving tracking, field-of-view, display technology, and explores new interaction strategies that may enrich the user experience.

In another approach, tangible artifacts are combined with (immersive) virtual environments, in what has been referred to as Tangible Virtual Reality (Tangible VR). Tangible Virtual Reality diverges from other Mixed Reality approaches by leveraging tangible interaction research promoting bi-manual interaction, and collaborative approaches, usually with hand-sized objects as representational artifacts [188, 187, 136, 294]. However, these approaches have mainly focused on developing proof-of-concept applications and approaches, with less regard to analyzing the merits of combining tangibles with virtual reality.

2.1.3 Interactive Surfaces and Spaces

Research on interactive surfaces and spaces focuses on tracking user actions and objects upon a surface or within an interactive space. This area shares characteristics with ubiquitous computing, tangible AR, and tangible VR.

A number of tangible interfaces use interactive tabletops and their tracking mechanisms as basis for interaction. The Reactable system [53], explored in further detail in chapter 4, is an example. Reactable's family of systems for digital music performances combines tangible and multi-touch input upon an interactive tabletop.

Recent research within this area increasingly relates to combinations of input technologies. Some examples include integrating multi-touch and tangible input [165]; employing active tokens and interactive surfaces [264]; and combining gaze and touch [214].

Research also explores flexible and shape-changing interactive surfaces. Trasnform [149] is an example of a dynamic tangible display that transforms kinesthetically in response to the presence of physical objects, changes in data, and user's movements. Recent efforts also explore novel approaches such as water condensation [255], textiles [215], and food [299].

2.1.4 Ambient Displays

Initial research on Ambient Displays can be traced back to the conceptualization of Calm Technology, introduced by Weiser and his team at Xerox PARC in 1996 [279], and the inclusion of ambient media for communicating information in Ishii and Ullmer's vision of Tangible Bits [150]. A key example for demonstrating the concept was created by Natalie Jeremijenko, an artist-in-residence at Xerox PARC at the time. She designed an instrument for visualizing network traffic based on an actuated "dangling string" [279]. Also refered to as the "LiveWire", this instrument employed an eight-foot string connected to a small electric motor mounted at the ceiling. The motor was connected to an Ethernet cable. The motor rotated in response to the network traffic. At quiet moments, the strings would twitch every few seconds; when the nework was busy the string whirled wildly and produced noise. The instrument was installed at the corner of a workspace, and could be seen and heard by many offices, communicating information by taking advantage of peripheral cues.

In current research, most ambient displays utilize purely graphical representations on screens of various scales, though multiple projects employ tangible interfaces as ambient displays in workspaces [122]; in museums [262]; and investigating tangible peripheral interaction (e.g.) in classrooms [87], and in the home [284].

2.2 Tangible User Interfaces

Tangible interfaces represent a subfield of human-computer interaction concerned with approaches for giving physical, interactively manipulable form to digital information. The topic is also referred to as tangible user interfaces (TUIs), in the context of broader research investigating tangible interaction [150, 243].

A number of paradigms and frameworks for describing and defining the characteristics, qualities, and aspirations of this field have been developed by researchers. Following, I describe some of the frameworks that contributed to the conceptualization of tangible interfaces.

2.2.1 Graspable User Interfaces

Following the inspiring vision of the Marble Answering Machine by Durell Bishop [115], several research projects have explored the use of tangible or graspable media. These projects, developed in mid- to late-1990s, include work at Interval Research [101, 247], Suzuki and Kato's "tangible programming languages" at NEC [252], and Fitzmaurice et al. [128], which developed the concept of "graspable interfaces".

Graspable user interfaces [128] are defined as providing "physical handles to virtual functions", in which the physical handles serve as dedicated functional manipulators. Fitzmaurice et al. [128] describe the following characteristics of graspable interfaces:

- **Space-multiplexing** input devices can be classified as being space-multiplexed or time multiplexed. When only one input device is available (e.g. a mouse), it is necessarily time-multiplexed – the user must repeatedly select and then deselect objects and functions. By offering multiple input devices, so that input and output are distributed over space, graspable user interfaces allow for simultaneous, independent, and potentially persistent selection of objects. Therefore, space-multiplexing allows for concurrent access and manipulation with two hands or by multiple users.

- **Specific input devices** the use of input or output devices with rich affordances that are dedicated to a specific functionality and potentially embody that functionality.

- **Spatial awareness and recongurability** the use of physical input devices is inherently spatial. Input devices can be arranged and re-arranged spatially in a way that is also physically persistent. This allows users to leverage spatial awareness and reasoning as well as muscle memory.

2.2.2 Tangible Bits

In 1997, Ishii and Ullmer articulated and demonstrated the concept of tangible user interfaces. In their vision, Tangible Bits [150] defines systems that "bridge the gaps between both cyberspace and the physical environment, as well as the foreground and background of human activities". They identified three key concepts:

- **Interactive Surfaces** – transforming surfaces within architectural spaces (e.g., walls, desktops, ceilings, doors, windows) into human-computer interfaces;
- **Coupling of Bits and Atoms** – augmenting everyday graspable objects (e.g., cards, books, models) with related digital information;
- **Ambient Media** – using ambient media such as sound, light, airflow, and water movement to communicate information through the periphery of human perception.

Following Tangible Bits, in 2001 Ullmer and Ishii presented the first steps toward characterizing tangible user interfaces as a distinct research area [257]. They characterized tangible user interfaces as systems that "give physical form to digital information, employing physical artifacts both as representations and controls for computational media," and presented an interaction model and key characteristics for such interfaces.

2.2.3 Tokens and Constraints

In 2005, Ullmer et al. [259] articulated and illustrated a new approach for tangible interaction and digital information. This approach was called Token+Constraint, combining tokens and constraints. While tokens provided handles for representing and manipulating digital information, constraints provided means for representing structure (e.g. stacks, slots, racks), which guided users on how to manipulate the tokens onto a number of computational interpretations. In parallel, Shaer et al. introduced the TAC (Tokens and Constraints) paradigm [246], which provides a set of constructs and a high-level method for describing the structure and functionality of a broad range of TUIs. Later, TAC became the basis for a high-level description language, TUIML, and a software toolkit for TUI development [244].

2.2.4 Knobs, Tokens, Wheels and Dials

Following the conceptualization of Token+Constraints [259], and TAC [246], a number of tangible-enabled systems employ dial-like tangibles as representations and controls for cyberphysical associations. However, the use of knobs in computational systems has a long history. The electromechanical interfaces of the 1946 ENIAC computer incorporated hundreds of radial dials [228]. The mid-1950s SAGE system [126], Sutherland's 1960s SketchPad system [251], and many other early graphical interfaces prominently incorporated interaction via mechanical dials. These early uses employed permanently mounted physical dials either statically mapped to specific digital functions, or reassigned by the GUIs to which they were coupled.

In systems specially conceived as TUIs, interaction has most often not only employed radial rotation, but also translational repositioning on and off of augmented surfaces, in association with a variety of inferred computational semantics.

Tagged handles offered interchangeable, tracked knob-like elements with haptic feedback [183], and have often been used in audio contexts [155, 210]. Where tagged handles were labeled with radial arrays of shapes and textures, the wheels of Strata/ICC [260] and tangible query interfaces [258] labeled tokens with static text and visuals, and applied these to parametric navigation of diverse datasets. [183, 260, 258] structured knob interaction around fixed mechanical constraints, while Sensetable and ReacTable allowed tangibles to be sensed and graphically mediated through continuous manipulation across interactive tabletops [210, 155]. More recently, SLAP widgets [280] and Facet-Streams [152] have evolved the visual, domain application, and implementational strategies. In other variations, the smart tokens of [84] employed new commodity platforms toward realizing active knob-like tokens with dynamically updatable faces.

2.3 Capacitive Sensing for tangible tracking

Sensing the presence, identity, and position of physical artifacts is a central technical task for many tangible interfaces [257]. Sensing can be viewed in terms of contact and non-contact technologies. Contact sensors include electromechanical contacts and pressure sensors. Non-contact technologies include computer vision, magnetic sensing, and RFID/NFC [92, 258, 272, 297].

Some sensing technologies span both contact and non-contact regimes. For example, capacitive sensing was first primarily used in non-contact modes [250, 302]. However, beginning with work such as [222] and accelerating profoundly with the commercial release of Apples iPhone, iPad, and Android variants the contact mode has achieved near-ubiquity today. Rekimoto noted that capacitive grid sensing technologies make possible the sensing of minimally-tagged objects [222]. This observation has been exploited by numerous research [95, 98, 269, 285, 296, 297] and commercial [58, 44] systems since.

These capacitive tags can be regarded as having two electrically functional interfaces. With the first, most capacitive tags require contact by a users skin on their upper and/or side surfaces. Typically, this is the user's hand (occasionally with intermediaries such as gloves with conductive finger tips). Second, the lower side of capacitively tagged objects is typically in direct contact with the capacitive sensor (typically, the multi-touch screen). To distinguish capacitively tagged objects from touch by fingers, spatial [95, 98, 285] or temporal [297] multiplexing is typically conductively linked to one or more surfaces that couple through users' hands.

The more common of these modes, and the one which we employ, is spatial multiplexing. Here, two or more conductive, capacitively coupled points are positioned in a distinct constellation relative to each other. Different systems have employed two [285], three [95], and up to eight [98] conductive points in contact with the screen. This number is associated with capacitive token trade-offs including the physical size, distinguishable IDs, number of tokens, error-resilience, required physical pressure, materials and fabrication technologies employed, and mobile vs. fixtured use.

Up to this point, I have surveyed the broad theme of tangible and embodied interaction. The following sections explore two main themes present in this dissertation: Posters and Virtual Reality. Each explored in more depth in chapters 4 and 5 respectively.

2.4 Paper, and Computationally-mediated Scientific Posters

The tradition of writings on walls dates back at least 5,000-12,000 years [292, 204, 116] The modern paper poster was invented in France, in the mid-19$^{\text{th}}$ century. The medium was first recognized as an artistic expression by Jules Cheret, "the father of the poster," for which he received the Legion of Honor. Posters spread throughout Europe within a decade [185]. A specific display platform for posters, the Litfassseule (an advertising column), was invented by Ernst Litfass [220] shortly after the introduction of posters, and remains ubiquitous in urban public spaces throughout Germany. Initially used by artists, the distinctive properties of this medium was quickly recognized, with posters becoming common for advertising, commercial use, politics, and propaganda. Today, posters are commonly used in classrooms and by many research communities as a platform to display diverse scientific content across numerous venues.

In academic conferences, presenters typically stand near their posters for a specified period of time, and present the content to interested visitors. During the remaining time, posters are mostly unattended. The presentation and discussion is commonly between two people or a small group. In the medical community, posters are often presented consecutively; each person has a short period of time to present the poster to a small group, or there are poster sessions that consist of guided tours. [112].

The number of academic posters presented each year is likely to be in the millions [230]. As one effort toward an approximation, Rowe [230] notes that some 22,123 individual universities and institutions of higher education are identified by Consejo Superior de Investigaciones Cientificas (CSIC) [274]. In Rowe's estimate, if each of these institutions hosts at least one annual conference with about 50 posters, the million-poster mark is easily reached. In addition to large 2-D paper prints, cloth as well as digital posters have been introduced in recent years. Some conferences allocate one or more slots for short poster presentations. These poster presentations can include all posters, or a small number of posters that have been selected by the organizing committee. Some conferences use video booths distributed throughout the venue with looping short videos of the posters. The latter represents an interesting approach, especially for conferences with a large number of posters, where it is not readily possible to read all the abstracts.

Others have explored computationally-mediated platforms for poster presentations at conferences [118, 112, 231, 205]. De Simone et al. [112] investigated such a platform in which images could be zoomed during presentations.

The MediaPoster [231] explored the combination of linked documents and images with a system that replaced paper posters with interactive LCD displays. To illustrate a conference employing similar platforms, the Society for Neuroscience has experimented with interactive posters in their annual meetings since 2013. In 2015, the conference in total hosted more than 12.000 posters, of which a small fraction were dynamic posters. Their posters employ flat-screens, and can display static slides, videos, and interactive charts and graphs [205].

Commercial solutions for the creation and presentation of digital posters have also emerged. With Multieposter [14], authors submit digital content (PDF or PPT files) using an online portal, and an specialized team generates the digital poster. Das Terminal [7] provides an online management tool in which authors themselves create the digital posters. Das Terminal also provides the hardware (stands and large displays) to present the posters. Similar to one of my approaches described in chapter 4, presenters use tablets to interact with the content. In the classroom, Cook et al. [109] had undergraduate students create HTML-based digital posters with interactive content using Google Sites [9]. For the same purpose, a number of websites exist that generate digital posters [11, 12, 2, 5]. Many target young users and have several pre-defined templates that can accelerate the creation of the posters.

Virtual worlds have also been explored in the context of learning activities, posters sessions and conferences [125, 175, 271]. Without real world constraints, poster sessions can occupy tall buildings [175], or spread along many streets [125], with users instantly teleporting to engage desired posters.

Regarding the design of posters, recently Pedwell et al. [211] applied multimedia learning theories to define a framework for best practices in poster design. This framework is especially relevant for computationally-mediated posters. I am unaware of poster-related platforms that combine forms of multi-touch and tangible interaction.

2.5 Virtual Reality

2.5.1 Combining 2D and 3D Representations and Interaction Modalities

For decades (perhaps more), the visualization of 2D data within 3D environments has been explored. Cone Trees presented animated 3D visualizations of hierarchical information [226]. The Perspective Wall is a technique that folds wide 2D data layouts into 3D visualizations presenting a center panel for details and two side panels for context [182]. While not considering immersive virtual environments (IVE) as we currently do, insights and observations such as the fact that computer screens are quite small when compared to "real-world" workspaces and that workspaces are limited by the human size and perception capabilities [182] may apply to our approaches that consider IVEs.

Approaches that explicitly combine 2D and 3D interactions have also been explored. Space-Top employs a see-through desktop display to combine 2D and spacial 3D interactions [174]. More recently, a hybrid 2D/3D interface has been proposed for radiological diagnosis. The system combines a stereoscopic display, a separate 2D display, mouse and keyboard onto a single interface [184].

This system has many intersections with the system described in section 5.5. Content is displayed by the screen that best suits the nature of the content (e.g., long texts are preferably displayed by the 2D screen).

Second Life has also been explored to bring 2D-native content to virtual environments. Sloodle adapts the interface of Moodle [26] to an immersive virtual environment [180]. This approach diverges from ours since it “replaces” the 2D with the VR interface.

Chapter 3

Combining Fabrication and Sensing Approaches for Tangible Knobs

"The coolest toys don't have to be bought; they can be built. In fact, sometimes the only way they'll ever exist is if you make them yourself." Adam Savage

"A Bostonian gets hopelessly lost on a back road in Maine, his map and the directions he was given completely useless. A little ways up the road he sees a farmer mending a fence, so the Bostonian stops to ask for directions.

[long dialogue ensues]

The farmer pauses for a while longer, and then looks at the Bostonian, 'You know what, now that I think of it, really, you can't get there from here.' " [41]

This chapter discusses work related to creating the building blocks for subsequent cyber-physical interfaces explored in this dissertation. I discuss the development of several active and passive dial-like forms, which can function as stand-alone entities, or in combination with mass-market (commodity) capacitive multi-touch devices, as well as a number of other sensing strategies for tangible knobs.

In the LAVA heuristics, legibility can be viewed as textual, form, and lychian legibility. In the context of tangible dials and knobs, textual legibility may relate to the use of texts, icons, or other representational forms sometimes understandable only by users, sometimes by machines, or both, in static and dynamic strategies. Forms are somewhat constrained when considering dials, with a number of variations on cylinder-like artifacts that embody rotational affordances. Perhaps more interesting is the concept of lychian legibility. It introduces the notion of legibility as a combination of visual, shape, material, and performative characteristics, all contributing positively or negatively to legibility. This multi-faceted notion serves as guide for the development of many of the systems in this dissertation, including the dials and knobs described here: at times, a single approach may not suffice to promote the level of engagement, interaction and legibility desired, in other words, *"You can't get there from here."*

I begin by exploring a number of design and fabrication approaches for passive dials, e.g. laser cut and 3D printed, embodying several strategies toward promoting user and computational legibility, in especial utilizing passive dials in combination with capacitive commodity devices. However, static information and passive elements can be limited in their ability to communicate, and allow for the development of engaging tangible systems. Dynamic displays, and embedded computational modules can enhance and complement actionability and legibility. Following several efforts involving passive dials, a number of active and hybrid dials were realized. Fig.3.1 depicts a number of dials and knobs developed.

Figure 3.1: **Survey of engaged knob platforms** *Several knobs developed and engaged. Dials are fabricated by combining of laser-cut, 3D printed elements, with and without embedded hardware. Some are passive, some are hybrid, and others active.*

3.1 Exploring General Purpose Tangibles

Regarding special purpose tangibles, perhaps a majority of publications to date explore distinctive physical forms. From a general purpose tangibles perspective, cubes, cylinders, marbles, spheres, and several other geometrical forms have recurred as common patterns not only in the tangibles literature, but also going back hundreds or thousands of years, from clay accounting tokens [235] to Froebel's gifts [130], and far beyond.

I next explore several past and present research-related and commercial products which employ general purpose tangibles. These examples served as inspiration and guide for our choice of creating tangible systems involving cylindrical objects.

3.2 Academic Variations

3.2.1 Marble Answering Machine

In 1992, Durrell Bishop, then a student at the Royal College of Art, devised a new design for an answering machine which is considered one of the first tangible user interfaces (TUIs), and has had arguably great influence in the field. Interaction with the answering machine evolves around a set of spheres, or marbles [115].

Each time an incoming voice message is recorded, the machine releases a marble. The order of the marbles indicates the order in which the messages arrived. Messages can be played back by putting a marble in a small dent. If the message is for somebody else it can be placed on a small dish to the side that can be labeled with names of different persons. The telephone itself also has a small receptor area for the marbles and by placing a message there, the original caller gets called back (Fig.7.3).

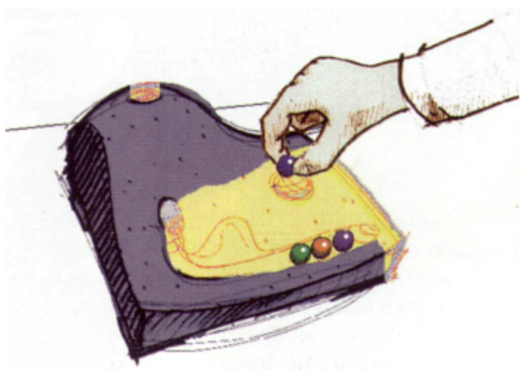


Figure 3.2: **Durell Bishop's Marble Answering Machine (1992)[115].** *Considered one of the first tangible user interfaces (TUIs), it employs general purpose spheres or marbles for interaction.*

3.2.2 ReacTable

The ReacTable [155] is an electronic musical instrument with a tabletop tangible user interface, which was developed within the Music Technology Group at the Universitat Pompeu Fabra in Barcelona. Conceived in 2003, the Reactable was presented for the first time in a public concert in 2005, and reached the "real world", and the rock stadiums after being hand-picked by Icelandic songstress Björk for her 2007 world tour. The company Reactable Systems was founded in 2009.

Interaction with the ReacTable is done with several geometric shaped tangibles. ReacTable's knobs can be categorized into six different functional groups: audio generators, audio filters, controllers, control filters, mixers and global objects, each associated with a shape (Fig.3.3). The Reactable tangibles employ general purpose shapes such as cubes and cylinders, and each face of the tangibles are marked with *fiducial markers*. Fiducial markers are specially designed graphical symbols, which allow the easy identification and location of physical objects with these symbols attached [91]. The primary sensor component for the ReacTable is the reacTIVision framework [158], which has been recognized with the "2016 Lasting Impact Student Award" for its broad and lasting impacts in the field of tangible user interfaces.

Figure 3.3: **ReacTable (2007)[52].** *The Reactable was conceived and developed since 2003 by a research team at the Pompeu Fabra University in Barcelona. Music can be produced collaboratively with the manipulation of tangibles of several geometrical forms, such as cylinders and cubes.*

3.2.3 Facet-Streams

Facet-Streams is a hybrid interactive surface for co-located collaborative product search on a tabletop [152]. The focus of Facet-Streams is to combine tangible and multi-touch interaction with information visualization techniques to support diverse strategies and collaboration styles, during product search. A goal of Facet-Streams is to turn these activities into fun and social experiences.

Facet-Streams employs two classes of general purpose cylindrical tokens. One to select facets of a search, and the other to display results (Fig.3.4).

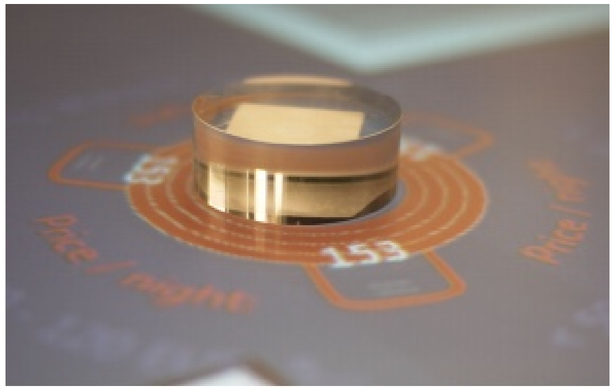


Figure 3.4: **Facet-Streams (2011)[152].** *Cylindrical tokens are used to select facets and display results form a query on top of a multi-touch surface.*

3.2.4 Sparse Tangibles

Sparse Tangibles [84] represent another member of the class of tangible systems which support query construction. Sparse Tangibles employ cylindrical active tangibles which embed smart-swatches into 3D printed custom cases and sensors, to allow query construction on and off the multi-touch surface. Sparce Tangibles primarily support cross-platform, collaborative gene network exploration using a Web interface, focusing on creating a fun, useful, and easy to use collaborative experience.

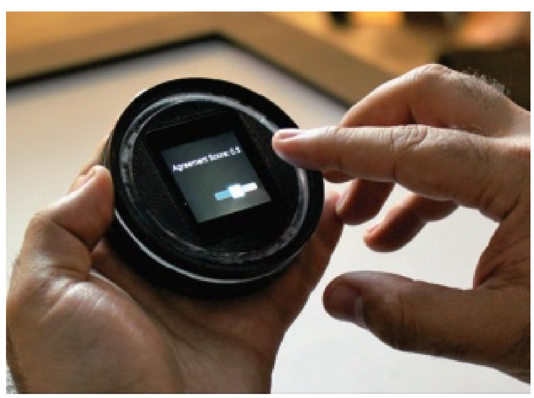


Figure 3.5: **Sparse Tangibles (2016)[84].** *Cylindrical active tangibles embedding smart watches are used in query contruction for gene network exploration on a multi-touch surface.*

3.3 Commercial Variations

Commercial industry has, especially of late, introduced many mass-market variations upon dials: fixed, like SGI's Dial Boxes [36]; wired, like Griffin's PowerMate [10]; and wireless, like Microsoft Surface Dials [45], Dell's Totems [35], and many others. This makes the present seem an interesting moment to explore synergies between community and commercial forms.

We explore five examples of commercial systems which incorporate knobs or dials, from the early 1946 ENIAC Compurter, to recent products released to interoperate with current multi-touch screens.

3.3.0.1 Eniac Computer

The Electronic Numerical Integrator And Computer (ENIAC) was built in 1943-45 at the Moore School of the University of Pennsylvania for the War effort by John Mauchly and J. Presper Eckert [203]. ENIAC was the first general-purpose electronic digital computer. It was 150 feet wide with 20 banks of flashing lights.

The ENIAC was not a stored-program computer; instead, it was a collection of electronic adding machines and other arithmetic units, which were originally controlled by a web of large electrical cables [203]. Programming the ENIAC involved a combination of plugboard wiring and three "portable function tables". Each function table had 1200 ten-way switches or knobs, used for entering tables of numbers.

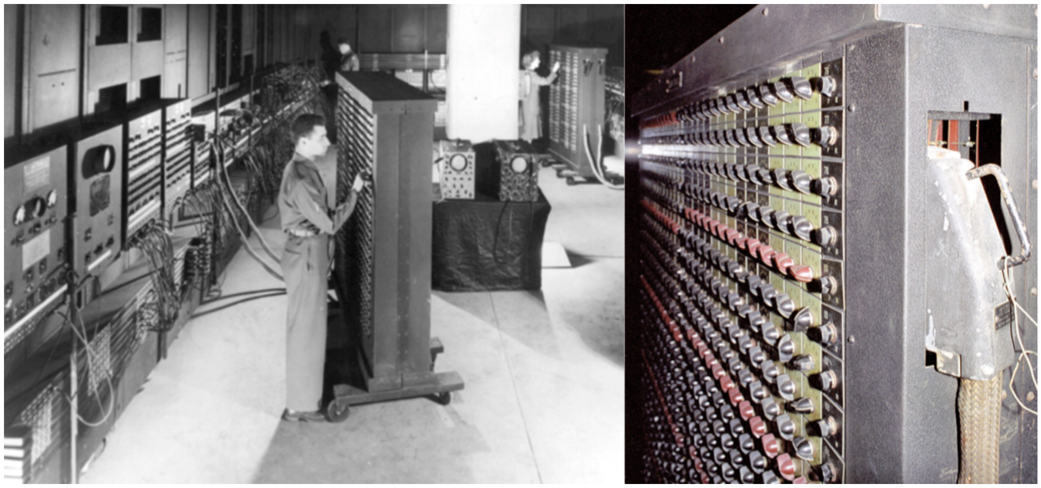


Figure 3.6: **ENIAC (1945) [228, 106].** *(left) View of the room where ENIAC was programmed and operated. In the center, one of the three "portable function tables". (left) Detail of a function table, with 1200 knobs.*

3.3.0.2 SAGE System

In early 1950, the military concluded that the manual air-defense system in use at that time could not adequately coordinate use of the improved hardware against the growing enemy threat. The Semiautomatic Ground Environment system (SAGE) was developed to 1) maintain a complete, up-to-date picture of the air and ground situations over wide areas of the country, 2) control modern weapons rapidly and accurately, and 3) present filtered pictures of the air and weapons situations to the Air Force personnel who conduct the air battle [126].

When it was used in its full capacity, air defense with SAGE was conducted from about thirty direction centers located throughout the United States, operated by over one hundred Air Force officers and airmen. Most of these men would sit at consoles directly connected to the computer where they received status data, and were able to direct the computer at each console (Fig.3.8). In the absence of modern multi-touch screens, consoles were composed of a large round CRT display, and a light pen. Several keys and special purpose cylindrical knobs were used to configure the machines.

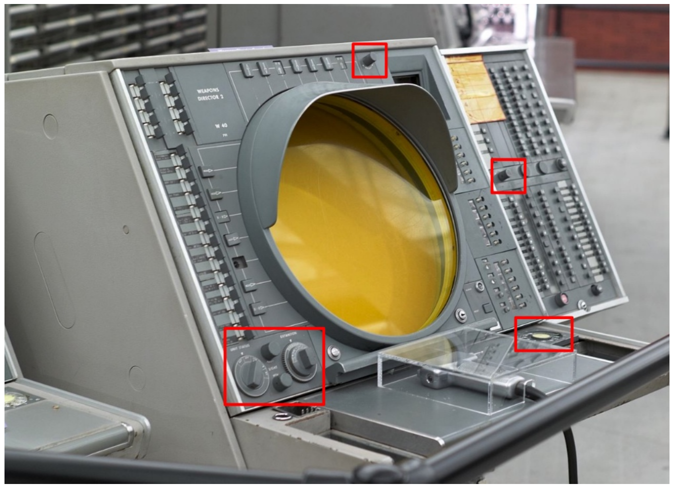


Figure 3.7: **SAGE (1954) [107].** *A SAGE (Semi-Automatic Ground Environment) terminal used during cold war to analyze radar data in real time to target Soviet bombers. The light pen is resting on the console. Dials and knobs have been highlighted in red. Located at the Computer History Museum in Mountain View, California.*

3.3.0.3 SGI's Dial Box

With the popularization of Graphic User Interfaces (GUIs), special purpose knobs lost most of their popularity, especially in the realm of personal computers. However, general purpose knobs and dials still found their way into niche markets. A dial box is a computer peripheral for direct 3D manipulation (e.g.) to interactively input the rotation and torsion angles of a model displayed on a computer screen [36]. Dial boxes were common input tools in the first years of interactive 3D graphics and they were available for Silicon Graphics (SGI) or Sun Microsystems and sold with their workstations. Although for many years they were entirely replaced by standard computer mouse interaction techniques, fans and enthusiasts still keep libraries and sample code in modern languages, besides pin-out diagrams so that these peripherals can continue to be used as computer architectures and operating systems evolve [36].

A standard SGI's Dials box has 8 dials mounted on a plate. The plate is set upright with the help of a stand and usually located next to the computer screen for convenient access. The connection to a computer is made via the serial port (RS-232).

Figure 3.8: **SGI's Dials Box (1980's) [108].** *SGI's Dials Box containing eight general purpose dials. Still compatible with modern systems (e.g. OSX) with libraries and code developed by DIY programmers and practitioners.*

3.3.0.4 Microsoft Surface Dial

The Microsoft Surface Dial [45] is an active general purpose cylindrical dial which can be used with several Microsoft Windows 10 programs. Although it is primarily targeted at digital artists, it represented the first instance in several decades in which a dial-like tangible was integrated into a mass-adopted operating system, and mass-marketed to the world.

We have been able to use the Microsoft Surface Dial in several instances of our own work, including on- and off-screen, augmenting it with 3D printed parts, and interfacing it with virtual reality applications. Several of our efforts aim at showing that this niche object can be employed in several other areas of application, beyond its original intended use.

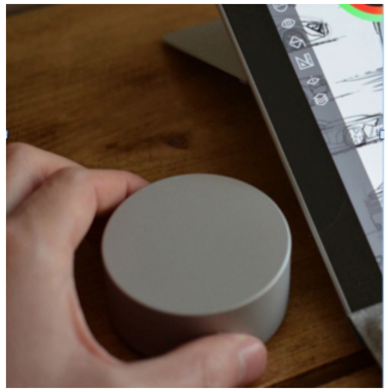


Figure 3.9: **Microsoft Surface Dial (2017) [45].** *The Microsoft Surface Dial can operate on- and off-screen, and is integrated with the Windows 10 operating system. The Microsoft Surface dial has enabled several tangible applications developed by us.*

3.3.0.5 Dell's Dial Totems

While the Microsoft Surface Dial is an active device, Dell's Dial Totems [35] are passive dial-like devices. Therefore, they can only work on-screen, while physically in contact with a multi-touch surface. Dell's Totems utilize Windows 10 native support for tangible dials, and were specially created to operate with the Dell Canvas multi-touch surface.

Similar to our own work, which began in late 2014, Dell's Totems (released in 2017) employ a sensing strategy in which a constellation of five touch points are identified by the interface system, determining their orientation and position. Our tokens, which will be described in detail later in this chapter, employ constellations of three touch-points for identification, orientation and position.

Figure 3.10: **Dell's Dial Totem (2017) [35].** *The Dell Dial Totem is a passive capacitive device and can only operate on-screen. Dell's Dial Totem represents another instance of a general purpose cylindrical dial-like commercial tangible device created for current hardware and operating systems.*

3.4 Exploring Design, Tracking, and Fabrication Approaches

While the cylindrical shape of tangible dials and knobs can be commonly found both in the industry and academic work, there isn't a single standard for building and interfacing tangible dials with computationally-mediated systems. While some might aspire for such standard for tangible dials to emerge, we investigate possibilities and interoperability between many different variants. In resonance with several of the academic and commercial approaches, I illustrate some platforms that work on commodity multi-touch devices, which operate with custom and commercially available knobs. I also introduce variations on knobs fabricated by laser cutters, 3D printers, and variations upon commercial forms.

3.5 Designing the Knobs

Our research group has a long history in developing tangible interfaces. Some have involved passive tangibles, while others active electro-mechanical systems. The majority of them, however, were manually crafted knobs. In my approach to create passive knobs, I adopted a *reproducible approach* for general purpose knobs, which allow multiple knobs to be assembled faster and more uniformly than the manually fabricated ones. The knobs developed are sensed by commodity, widely available hardware platforms that are capable of capacitive sensing, such as tablets, laptops, and smart-phones; eliminating the necessity of (usually expensive, over $5,000) custom-built, or special-purpose hardware.

3.6 Shape, Size, and Materials

These knobs have been designed considering the LAVA design heuristics [261], as well as design criteria within [139]: shape, size, materials, and usage context. In terms of shape, as exemplified before, the use of cylindrical objects in computational systems has a long history, including in the TUIs realm; This informed the design of round knobs with a flat top and bottom, indicating the affordance of rotation. The knobs' size is comfortably held by most teenagers and adults, while also being suitable and safe for children, with the possible exception of the very young. Knobs are ~6 cm in diameter.

Capacitive sensing requires designing knobs in which some or all components are conductive. We use acrylic sheets, wood, and metal shims when fabricating with laser cutters, and conductive polylactic acid (PLA) thermoplastic when 3D printing. The choice of materials, size, and shape were also dictated by the task, and target environment defined for the tangibles. Sometimes I adopted colorful materials, sometimes wood, according to the context.

3.7 Engineering Considerations

Fabricating passive knobs for multi-touch screens requires careful design and engineering considerations. To distinguish capacitive objects from finger-touches, spatial [95] or temporal [297] multiplexing is typically used. As mentioned in section 2.3, the more common of these, and the one I employ, is spatial multiplexing. Here, two or more conductive, capacitively coupled points are positioned in a distinct constellation relative to each other. Different systems employ different numbers of contact points, which leads to a number of trade-offs including in physical size, distinguishable IDs, number of concurrent tokens, etc.

Two other broader technical constraints shape the functionality of capacitive tags. First, multi-touch capacitive screens typically incorporate a number of constraints relative to their anticipated use and function. For example, most capacitive tablets presently support a maximum of approx. 10 simultaneous sensed touches (presumably in anticipation of a single user using at most two five-fingered hands) and are presently tuned to sense contacts at a range of sizes comparable to fingertips.

Second, any system that relies upon electromechanical connection is influenced by a variety of properties that govern the quality of electrical contact. A phenomenon known as switch bounce occurs whenever mechanical jitter causes intermittent disconnection of the circuit [79]. This temporary loss of electrical contact is known to cause glitches in systems that inadequately filter this form of noise.

This is compounded by several additional challenges. First, some present multi-touch capacitive surfaces are glass, which may be scratched by metal. Second, especially if more than three conductive tags are utilized, simple geometry and mechanics suggests all points may not be in constant contact with the sensing surface.

3.7.1 Tracking Knobs: Defining Touch-point Patterns

The design I employ incorporates constellations of touch points, sometimes using stylus tips, sometimes flat conductive rubber pads; that may be rigid or pliable. I have chosen to employ patterns defined by three touch points, which describe a plane, and allow the knobs to be uniquely identified. Position and orientation can also be sensed by the underlying software. Figure 3.11 shows the patterns described by the knobs with three distinct IDs. Without recurring to any additional strategy to uniquely identify tokens, I have explored spatial arrangements for the three touch-point patterns that support 8 to 16 distinct ids. Most multi-touch surfaces perform well with the 8-id arrangements, however, with 16-ids, reliability varies widely according to the model and manufacturer of the multi-touch surfaces. Most of the designs are based on the 8-id variation. Appendix A contains a template for the 8-id touch-point patterns.

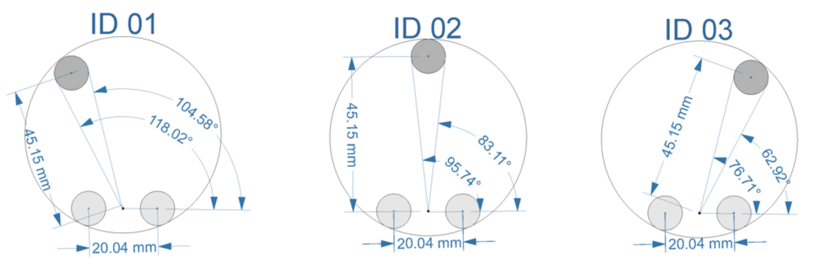


Figure 3.11: **Three touch-point patterns for tangible knobs on capacitive multi-touch screens.** *The patterns define triangles. Distances and angles between touch-points are used by the underlying software to identify each pattern.*

3.7.2 Selecting Touch Pads

As mentioned previously, two challenges when defining how to physically couple the tangible knobs with multi-touch screens are: securing good electro-mechanical connections (eg. to avoid signal jitter), and selecting materials which will be in contact with the multi-touch surfaces that won't scratch them. This is important since most multi-touch surfaces are made of glass. I have applied three different variations of stylus tips, and successfully employed conductive rubber as touch pads for knobs.

The first two examples (Fig. 3.12a and b) are large and small metallic fiber stylus tips from the Swedish company Friendly Swede [29]. These stylus tips create good mechanical contact, while allowing the tokens to rotate freely on top of glass surfaces. Although these tips perform well, they are relatively costly (approx. $1,00 each), and I have, so far, found just a single supplier. I sought to find alternate approaches that could potentially be less costly and more widely available. Figure 3.12c depicts a rubber stylus tip. This variation is cheaper (approx. $0.60 each), and can be found from several suppliers. The down side is that they are not as pliable as the metallic fiber ones, causing some electro-mechanical instabilities. Another negative factor is that they do not slide as freely on top of glass screens. These two elements combined mean that the user is required to apply pressure while holding the knob against the multi-touch surface, in order for it to work properly. On a third variation, I employed conductive rubber. While I was skeptical at first – since it affords very little pliability – our ability to fabricate pads with different sizes (typical size employed was 10 mm in diameter), made this a viable choice. Several informal empirical evaluations I performed, asking users to qualify which version performed, or felt better, showed no difference between the metallic stylus tips and the rubber pads. Two advantages of the rubber pads is that price is lower than the previous two options, and the material can be easily found on specialized stores. Metallic fiber stylus tips and conductive rubber pads were commonly used to create the capacitively sensed artifacts described in this dissertation.

Figure 3.12: **Choices of stylus tips for passive knobs.** *a) Large metalic fiber stylus tips. b) Small metalic fiber stylus tips. c) Rubber stylus tips.*

3.8 Algorithm and Implementation

To identify knobs containing three touch-point patterns, I adopt a simple algorithm. This algorithm consists of identifying the base of the triangle defined by the three touch-point patterns, calculating the mid-point between them, and finding the angle and distance between the mid-point and the third (top-point) of the triangle. Once distance and angle are found, they are compared to a pre-defined list of values, which relates distances and angles with knob ids. By construction, the base of the triangle is the side that has the shortest length. Algorithm 1 shows the pseudocode.

Algorithm 1 Algorithm for identifying three touch-point patterns on capacitive multi-touch screens

```
for Each group of three touch points received do
    Identify the base of the triangle described by the three touch points
    Find the mid-point between the two points of the base
    Calculate the distance between the mid-point and the third point of the triangle (top point)
    Calculate the angle between the segment of line formed by the midpoint and the top point,
and the segment of line formed be the midpoint and the right point of the base
    Compare the angle and distance found to a list of angles, distances and knob ids
    Return the knob id
end for
```

I have written software libraries with the Python programming language [23] and the Kivy NUI framework [17] to insulate client code from the details of token identification and tracking. Python and Kivy were chosen due to their broad support of contemporary multi-touch devices. I have also written libraries for Unity 3D, in C-Sharp, to allow integration of tokens with virtual reality environments. Python sample code for the identification of tokens can be found in the Appendix C.

To track the knobs, two other elements must be obtained: position and orientation. Once a knob is identified, the coordinates of the triangle described by the knob are analyzed and its *centroid* is calculated to indicate the position of the knob. Given the coordinates of the three touch points describing a triangle ABC, the coordinates of centroid O are given by the following equation [97]:

$$O_x = \frac{A_x + B_x + C_x}{3} \quad \text{and} \quad O_y = \frac{A_y + B_y + C_y}{3}$$

where $\mathrm{A_x}$ and $\mathrm{A_y}$ are the x and y coordinates of the touch point A, and the same follows for points B and C.

To obtain the orientation of the knob, we calculate the angle between the base of the triangle (side with smallest length), and the x-axis of the coordinate system used in the client software (e.g. Kivy, or Unity 3D).

3.8.1 Challenges of Tracking Touch Points on Capacitive Commodity Multi-touch Surfaces

Commodity multi-touch surfaces are primarily calibrated to sense finger touches. The sensing of a finger touch is inherently noisy; the signal coming from the touch sensors is usually filtered by the operating system underlying software before it is raised as a callback, with coordinates, to a client software. The algorithm for pattern identification must, therefore, be prepared to account for an "error" in the measured distances between the touch points. In this approach, this is achieved by comparing angles and distances to a range of values, instead of a single number for angle and for distance. I found that common commodity multi-touch surfaces operate well with a tolerance of +/- 10% of the calculated value.

Another challenge of tracking passive knobs on capacitive multi-touch screens is identifying when knobs have been removed from the surface by the user, and when they have been left on top of the surface, without the user actively touching them. Being able to identify *present-untouched* versus removed tokens is an important feature to create tangible interfaces which react in meaningful ways to user's actions and tangibles they work with.

Toward solving this problem, when the user removes a knob from a multi-touch screen, the system identifies a quick decay on the signals coming from the three touch-points of the knob, and

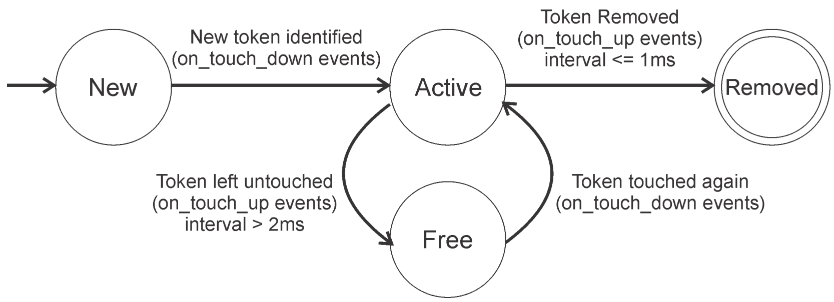


Figure 3.13: **Finite state machine for identifying untouched tokens left on top of a multi-touch screen versus a token that has been removed from the surface.** *The difference in the intervals between events allow the client interface software to identify a token which has been left untouched (Free) and a token which has been lifted from the surface (Removed).*

issues callbacks (e.g. on-touch-up calls) indicating that the points are not present anymore. The client software can capture these callbacks and act accordingly. Usually the callbacks coming from the removal of a knob occur almost simultaneously for all three points; within milliseconds between them. When users remove their fingers from a knob which remains in contact with the multi-touch surface, at first the three touch-points remain capacitively charged. A couple of milliseconds later a signal decay starts to occur. Such decay occurs much slower and irregularly (meaning that decay occurs at different rates between touch points) than when the knobs are removed from the surface. Callbacks from the operating system occur in intervals which are typically greater than 2 milliseconds. By analyzing the interval between each callback indicating that the signal of a touch-point has been lost, I am able to distinguish between when knobs are removed, and when they are left untouched on the surface. This strategy is visually represented by the finite state machine in Figure 3.13.

3.9 Fabrication Approaches: Laser Cut Knobs

Having defined a sensing approach for the knobs, and the pads that would be mechanically in contact with multi-touch screens, I created a design for laser cut knobs.

Fig.3.14 depicts a knob fabricated with a laser cutter. In my approach, I sandwich a central conductive ring, used to establish electrical contact with a user's hand, with non-conductive layers. These outer layers support human legibility (the upper visually-inscribed layer) and computational legibility (the lower layer). The lower layer structures a constellation of touch points, realized as threaded conductive mesh stylus tips. The pattern described by these tips is defined by an

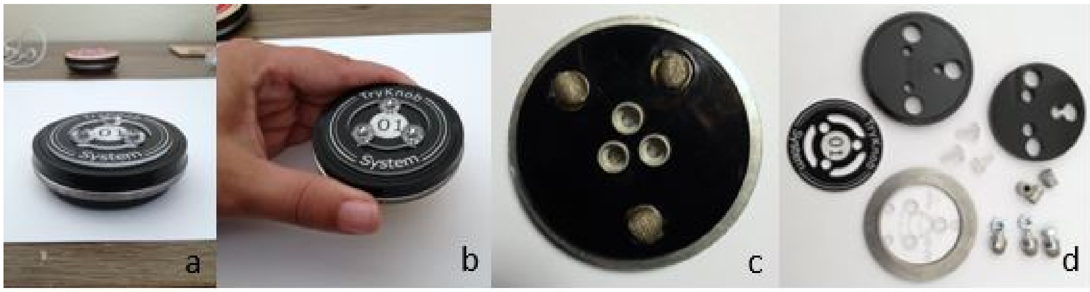


Figure 3.14: **Laser cut dials.** *a,b) Detail of the top of a laser cut knob. c) Detail of the bottom. d) The parts that compose a laser cut knob.*

acrylic guide piece that is positioned within the internal circumference of the metallic ring. The non-conductive layers also serve as mechanical fixture plates for connecting the ensemble structure together. The pieces are held together by three pairs of rivets and screws.

The small size of the pieces employed suggests this design can be replicated with most laser cutters, as well as other fabrication tools (e.g., CNC mills and routers, water jets, etc.) from a variety of materials. Fig.3.15 lists the parts involved. To allow easy reproduction of laser cut knobs, I've developed a design and fabrication guide, which can be found on Appendix B. The guide aims at facilitating the fabrication of laser cut knobs as described in this section.

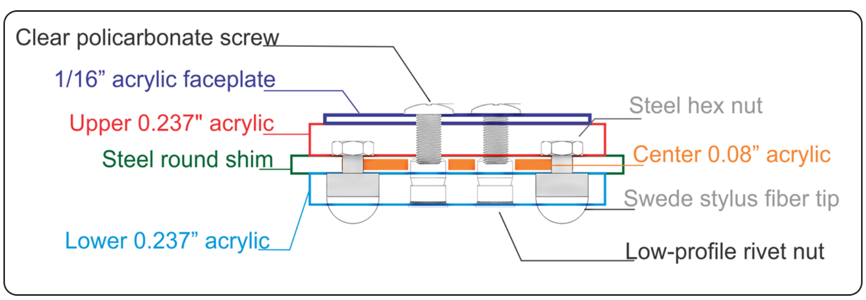


Figure 3.15: **Parts which compose a Laser cut dial.** *The laser cut dial is composed of nine distinct parts, and 17 parts in total.*

3.10 3D Printed Knobs

While my initial approach with laser cut knobs seemed altogether effective, the fabrication and assembly of the multiple components can be laborious, the resulting knobs sometimes were too heavy, and not all research groups or practitioners have access to laser cutters. As an alternative, I created knobs based on 3D printing technology, a technology that has achieved increased popularity in the past few decades. User-reported numbers show there are currently nearly 1,400 active maker spaces, 14 times as many as in 2006 [48]. With 40% reporting 3D printers, and only 26% reporting lasers cutters as their most frequently used tools [48].

3D printing, also known as *additive manufacturing*, offers a new platform for creating knobs and tangibles in general. The three-dimensional body of a knob is generated by "slicing" the virtual model into two-dimensional segments and then printing the actual object layer by layer. Fabrication of 3D printed knob requires no external tools, and can be printed on-site within an hour. The level of complexity of a 3D printed knob design is limited to that of one's 3D printer and CAD (Computer Aided Design) skills. Chapter 3 explores 3D printing technology in depth.

To contrast the laser cut and 3D printed knobs, I first designed a 3D printed knob which is very similar in form to the laser cut ones (Fig. 3.16a and b). In terms of the number of components, our laser cut design requires the assembly of nine distinct components, while the 3D printed counterpart (in its simplest form) consists of only two distinct components and four parts in total. In terms of functionality, both approaches produce knobs which are very similar, however, aesthetically the 3d printed knobs are more limited. Even when printing with dual materials, the laser cut knobs are still perceived as more refined and interesting in general. Figure 3.16 shows a number of 3D printed knobs in diverse shapes, using only conductive PLA (Fig. 3.16a to g), or combining conductive and non-conductive materials (Fig. 3.16h).

Several 3D printers were used in the fabrication of our knobs: the mono-extruder Lulzbot Taz [42], the dual-extruder Makerbot Replicator 2X [55], and the FlashForge Creator Pro [6] were the most frequently used. I employed mostly conductive PLA thermoplastic to fabricate our knobs and couple the users touch to the capacitive screens. Table 3.1 shows some of the properties of the conductive PLA used. Later designs also explored combining regular (non-conductive) PLA with metallic grounding bodies connected to the touch points to couple the human touch with the capacitive sensing of multitouch surfaces.

Electrical Properties of Conductive PLA Filament	**Value**
Volume resistivity of 3D printed parts perpendicular to layers	30 ohm/cm
Volume resistivity of 3D printed parts through layers (along Z axis)	115 ohm/cm
Resistance of a 10 cm length of 1.75 mm filament	2-3 kohm

Table 3.1: **Electrical properties of conductive PLA filament** *These properties make them ideal to interact with capacitive multi-touch screens.* [4].

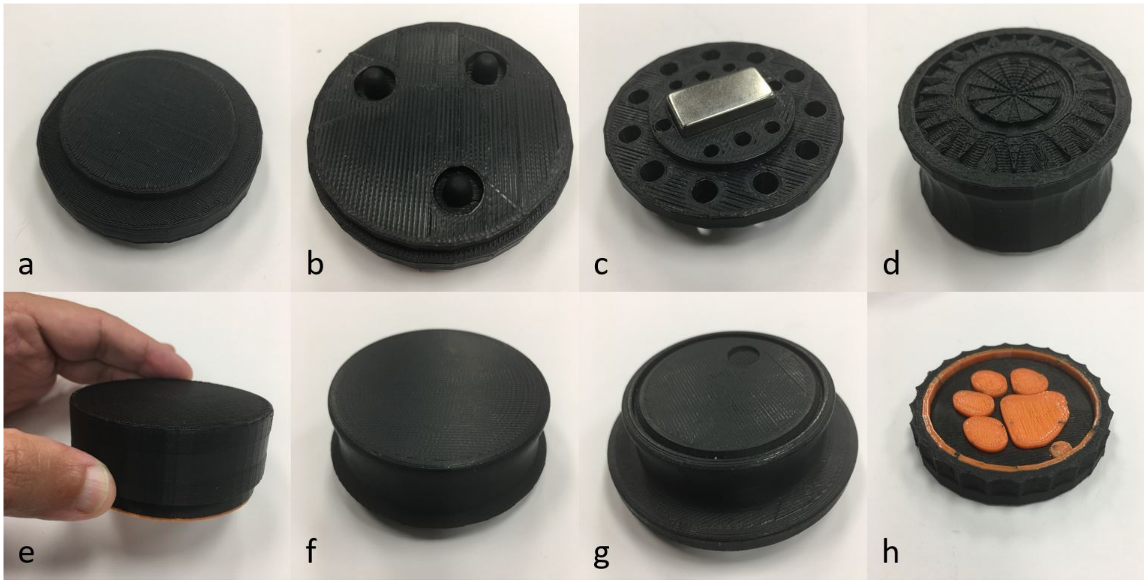


Figure 3.16: **Variations upon 3d printed knobs.** *All knobs are mostly black due to their fabrication utilizing conductive PLA thermoplastic. a) First 3d printed knob design. The design mimics the laser cut knobs to emphasize the reduction in the number of parts, and similarities in functionality. b) Bottom of the knob. It shows rubber stylus tips as pads. Other options such as metallic fiber tips and conductive rubber can also be used. c) 3d printed knob with added weight to enhance mechanical connection with screen. d, e, f, and g) Departure from the laser cut design. Details to ornament the top, and curvilinear shapes have been explored. h) Dual material 3D printed knob. The combination of conductive (black) and non-conductive (orange) PLA gives more freedom of design to create aesthetically appealing artifacts.*

3.11 Combining Laser Cut and 3D Printed Elements

After fabricating several variations of knobs which were 3D printed or laser cut, toward creating knobs with the best characteristics from both fabrication approaches, and supportive of the underlying theme of this dissertation, I explored designs which combine commercially available, laser cut, and 3D printed elements.

From a design perspective, following the "C" in the **C.R.A.P.** (**C**ontrast, **R**epetition, **A**lignment, and **P**roximity) principles of sound design, laid out by Robin Williams [287], I explored contrasts between the 3D printed thermoplastic, and the laser cut acrylic polymer. For conductivity purposes (and computational legibility), the body of the knobs are composed of the black opaque conductive PLA. This contrasts with the semi-transparent, shiny nature of some of the acrylic materials (Fig.3.17). Laser cut elements were also used to create textual legibility. Figure 3.17a shows a knob with a faceplate which has the words "Entrada Poster" engraved in a piece of bitonal matte

	Laser cut	3D printed	Laser cut + 3D printed
Functionality	good	good	good
Num. of distinct parts	9	2	approx. 4
Fabrication complexity	high	low	medium
Visual refinement	medium	medium	high

Table 3.2: **Comparison of properties of knobs fabricated with diverse approaches.** *Knobs combining fabrication approaches are functionally similar to the other two options, but are visually more refined, less complex than laser cut ones to fabricate, and require fewer components.*

acrylic [57]. While it is possible to emboss or deboss words with 3D printing, the resolution and level of refinement are not as good as what laser cut technology allows. Another strategy for legibility can be seen in Fig. 3.17b, c, and d, in which the semi-transparent acrylic was engraved with words, symbols, and icons.

To compare knobs fabricated with the different approaches, I analyzed the properties of *functionality, number of distinct parts, fabrication complexity, and visual refinement.* In terms of *functionality*, laser cut, 3D printed, and the knobs combining elements of both fabrication strategies perform similarly well. From a *number of distinct parts* perspective, laser cut knobs were more complex than the others, requiring nine elements. Purely 3D printed require just two parts, while the combined approach require on average 4 distinct parts. The same trend is followed when comparing *fabrication complexity.* Knobs with laser cut + 3D printed parts were not as complex as laser cut, but were a little more complex than purely 3D printed ones. We find the *visual refinement* of the laser cut knobs to be similar to the combined approach, with the 3D printed knobs not achieving a high level. Table 3.2 summarizes these properties.

3.11.0.1 Coupling Laser Cut and 3D printed Elements

Once the combination of 3d printed and laser cut elements was selected as a viable and desirable option to fabricate knobs, I started to investigate a number of coupling strategies. A simple strategy to connect 3d printed and laser cut materials is to use adhesives. This strategy has pros and cons. Coupling 3d printed and acrylic elements can be easily achieved with the use of cyanoacrylates-based adhesives, which are sometimes known generically as instant glues, power glues or superglues [234]. These glues work fast and produce a good connection between acrylic and thermoplastics (e.g. PLA and ABS). However, these type of glues can stain the acrylic during the application process, and more importantly they can be toxic [266]. Figure 3.17a and b show knobs in which superglue was used to attach laser cut acrylic pieces to a 3D printed body.

Later, I devised a method to eliminate the use of any adhesives, while creating aesthetically appealing elements. In this process, an acrylic piece can be embedded within a 3d printed part during the printing process. To achieve this result, the 3D model considers the space that is occupied by the laser cut element. During the printing process the operator of the 3d printer stops the print at a specified height, places the laser cut element inside the 3d printed piece that is in progress, and re-starts the 3d printing machine. As the 3d printer deposits hot thermoplastic filament on top of the laser cut element, it adheres to the piece, creating a firm bond that efficiently replaces the need for any adhesive. Figure 3.17c and d show knobs in which acrylic pieces were embedded in the 3d printed knob.

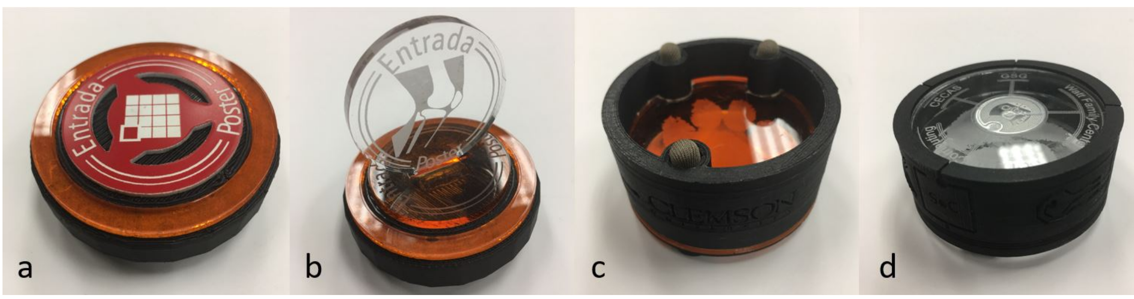


Figure 3.17: **Variations of knobs combining laser cut and 3D printed elements.** *The bodies of the knobs are 3d printed with (black) conductive PLA. a and b) knobs received different variations of laser cut face plates for readability. Laser cut elements were glued to the 3d printed body of the knobs. c and d) laser cut acrylic pieces were inserted during the 3d printing fabrication process, embedding the laser cut elements in the body of the knobs.*

3.12 Active and Hybrid Knobs

As discussed in the beginning of this chapter, static information and passive elements can only go so far to communicate, and allow for the development of engaging tangible systems. Here I describe efforts toward developing tokens and knobs that combine multiple mediation modalities, including *active* and *hybrid* variations.

Some of the design and fabrication strategies described here go beyond the scope of knobs, these strategies were also employed later, to develop other functional prototypes (e.g. the VR

Fishing Rod described on Chapter 5) which incorporate some form of rotational interaction. I define active tokens as those that embed some form of electronic component that is continuously powered internally or externally during its use, and hybrids those which embed electronic components that are inactive for most of the time, but can be awaken when in close proximity to external sources of power (e.g. RFID, and NFC tags).

Next, I explore some strategies toward creating active and hybrid knobs, and comment on the prototypes developed. I will describe three active devices: the *RGB token*, the *Active Challenge Coin*, and *Mobile Challenge Coin*, and two hybrid ones: the *Hybrid Challenge Coin*, and the *Augmented Surface Dial*.

3.12.1 Active Knobs and Dials

3.12.1.1 RGB Token

The RGB Token was developed in early 2016. The main goal of the project was to understand the software and hardware requirements to create functional active tokens, as well as, begin to explore active forms of sensing and legibility (including active visual and auditory feedback). While developing this device, the technical challenges were given priority, and less attention was given to aesthetics. Figure 3.18 details the components of the RGB Token.

As a hardware platform, I chose the Arduino Micro [23] as the micro-controller for the RGB Token because of the number of digital pins it offers (20 in total). This number of pins allowed connection with several other components to the micro-controller. The RGB token supports dynamic visual and auditory feedback, connection via Bluetooth, sensing of position, orientation, and an input button.

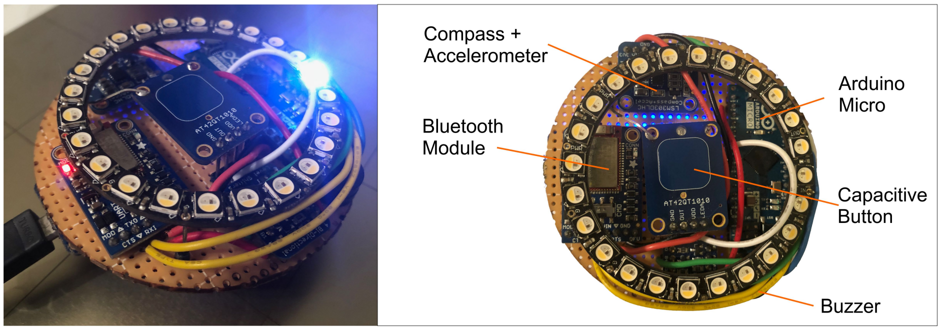


Figure 3.18: **RGB Token.** *The RGB Token contains a bluetooth module for data communication, a capacitive button for input, and compass and accelerometer for rotation and direction sensing. The 24-LED ring and the buzzer are capable of providing the user with visual and auditory feedback.*

For dynamic labeling the token, a 24-LED Neopixel ring [47] was installed. While this display choice was very limited in its capacity to convey information, due to its limited pixel count, it was soon noted that the LEDs could have advantages over other types of displays. While most displays are capable of showing detailed (iconic and textual) information at a close distance, but are less efficient at a distance, the LED ring provides high-level information (in contrast to detailed information), both at close range, and at a distance (e.g. across a room). Figure 3.19 contrasts the LED ring and high pixel count screens, considering the (L)egibility in the LAVA heuristics. This realization started to point at combinations of mediation strategies as optimal approaches, and was further explored with the *Active Challenge Coins*, and the *Mobile Challenge Coins*.

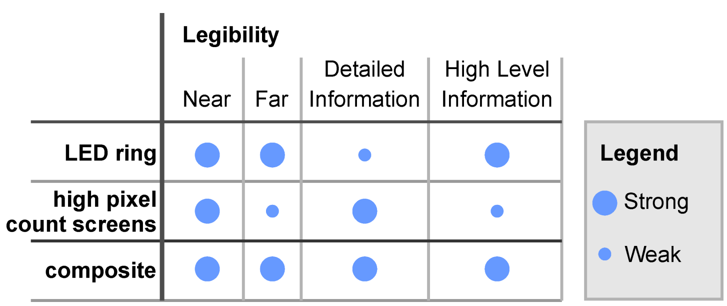


Figure 3.19: **Legibility comparison between LED ring and high pixel count screens.** *Led rings are legible both at near and far distances, being especially useful to display high level information. Small size high pixel count screens are better at displaying detailed information, at a close range. A composite device can potentially combine the existing strengths in a single unity with stronger legibility properties.*

While the LEDs provide user legibility, a combination of modules were added for computational legibility. A Bluetooth module was installed for communication; messages between the token and the host system are exchanged using the Open Sound Control protocol [293], and a simplified version of the TUIO protocol [17]. A triple-axis magnetometer is employed for sensing rotation and orientation. To sense position, I adopted an unconventional approach. I employ an Adafruit APDS9960 proximity, light, RGB, and gesture sensor [1]. This sensor is installed at the bottom of the knob, facing down. Its purpose is to read the color of the surface underneath the token. The interfaces which support the RGB Token were designed with areas in different colors. For example, by placing the RGB Token on top of a blue region, the zooming function is activated, a green region activates the rotation function. Using the same approach, the general position of the token is detected. By creating physical areas off-screen with different colors (e.g. with paper cutouts), the RGB Token is also capable of working on top of a desk. This feature is important since it frees screen real estate, and allows the RGB Token to work off-screen, for example, with interfaces that operate solely with vertical displays. As a source of input, a capacitive button was added to the top of the dial. The RGB Token shares a number of characteristics with Microsoft Surface Dials, described in section 3.3.0.4. A detailed comparison of both can be found in appendix E.

3.12.1.2 Active Challenge Coins

In the beginning of 2017, a new edition of active tokens was developed. This time, I aimed at developing tokens that were not just functional, but also aesthetically pleasing. These tokens were designed to work individually, or complement other tangible user interfaces (e.g. in conjunction with Challenge Books, described in chapter 7).

These tokens were named after *challenge coins*. A challenge coin is a small coin, bearing an organization's insignia or emblem and carried by the organization's members [32]. The tradition of challenge coins goes back hundreds of years. The Roman Empire rewarded soldiers by presenting them with coins to recognize their achievements [32]. Today we can find several examples of beautifully designed challenge coins celebrating sporting events, and achievements, and are often collected. Fig. 3.20 shows some examples of challenge coins.

Figure 3.20: **Challenge Coins.** a) United States presidential challenge coin [59]. b and c) Airman's coin circa 2001 [105].

Three variations on challenge coins were created. Fig. 3.21 depicts them. Fig. 3.21a, shows the first challenge coin developed. Active components were mounted on a 3D printed body, composed of three layers held together by screws and rivets. This layered approach allowed us to create a slim shaped token, that can hold several electronic components (e.g. Arduino module, LED ring, e-ink display). The body has a lateral opening which receives a micro-USB cable for data exchange, and powering the device. The first version (Fig.3.21a) contains an Beetle [24] Arduino-compatible micro-processor, which drives the Neopixel LED ring. The e-ink display that seats beneath the LED ring is not wired to the Arduino module, instead, images can only be changed by physically connecting the display to an additional (external) hardware interface for refresh. Although not ideal, this arrangement allowed validation of the design, and allowed me to understand requirements such as external and internal sizes, and overall feasibility of the artifact.

Once we were comfortable with the overall design, two challenges remained. The first, related to eliminating the necessity for the micro-USB cable for power and data; The second, actively driving the e-ink display. Toward overcoming these two challenges, two new variants were created (Fig.3.21b and c).

I adopted two strategies toward eliminating the necessity of the micro-USB cable. Initially, I added a small Lipo battery [197] to a thicker version of the challenge coin. Lipo batteries are typically used to power miniature radio controlled models of cars, drones, planes, and boats. The battery is able to power the device for approx. 15 minutes, with 6 LEDs lit at 50% brightness. This version, although effective, still required the use of the micro-USB for re-charging purposes. To eliminate this need, a second version of the challenge coin incorporated a copper coil for wireless charging the device (Fig.3.21b). While providing power to the device no longer required the use of a cable, data exchange for updating the LED lights and e-ink display still required a physical connection.

To drive the LED ring and the e-ink displays via a wireless connection, several components had to be changed. First, the Arduino Beetle did not have enough data pins to drive both the LED ring and the e-ink display. Moreover, it was not capable of any type of native wireless connection (e.g. wifi or Bluetooth). I exchanged the Beetle for a Wemos D1 Pro microprocessor [67]. This module is capable of wifi communication, and allowed the connection with both output components. On the negative side, the size of the coin had to be increased. For aesthetic reasons, I updated the LED ring from a 12-led ring to a 16-led ring. Fig.3.21c and d show this version.

The challenge coin presents several opportunities for id and position tracking. One option for tracking is to add conductive rubber pads at the bottom of the device for sensing on capacitive multi-touch displays. The coin's active e-ink display can be set to show markers (e.g. fiducials or QR codes), so that computer vision systems can track id, position and orientation in real-time. A similar approach can be taken by changing the pattern of lights displayed by the LED ring.

In terms of communication, once wifi connection is established, two approaches were explored. The first, exchanging information using OSC and TUIO-based messages. The second using REST APIs, with html-based applications. In both cases I was able to control the LED ring and e-ink displays in real-time, concurrently.

LAVA mediation engagements

One objective of this tangible is interweaving three forms of mediation, each differently engaging LAVA facets, into a composite that exceeds the capacities of any individual or pairwise approxima-

Figure 3.21: **Active Challenge Coins.** a) 12-LED tethered challenge coin. b) Active challenge coin equipped with wireless-charging. c) 16-LED active challenge coin equipped with wireless data communication via wifi showing graphic and textual information. d) BMW themed challenge coin.

tion. This is explored (albeit subjectively) in Figure 3.22. Here, the rows engage the three mediation facets of the coin: two active (epaper, LED), and one passive (the integrating physical construct); and when engaged as a composite. The columns depict the facets of LAVA. "Legibility" is again contemplated from two different spatial perspectives "near" (e.g., when viewed from "arm's length"); and "far" (e.g., when viewed in an adjacent collaborator's works-pace). Thus constructed, among the compositional mediating facets, I regard the epaper as contributing the highest legibility when viewed "near," and the lowest when viewed from "far," per the alternating strengths and limitations of text and icons as representational mediums. Conversely, similar to the discussed with the RGB tokens, when viewed from "far," the LED ring retains some level of legibility to its mapping - especially when viewed both as an ensemble of active challenge coins (allowing perceptual comparisons of "like" vs. "different"). In our view, when taken as a composite artifact, these relative strengths and weaknesses can counterbalance each other, yielding an artifact that is (aspirationally) legible in both the near and far-field realms of engagement.

Regarding actionability, taken by itself, I see the epaper display as holding, per Gaver's view a "false affordance" [131], or as we put here a "negative aordance" (hence the red negative label). Specically, with screen-based representations presently suggesting the capacity for touch interaction to many people, the absence of this capacity with our present screen (selected partly for its very modest cost) could setup prospects for an unmet expectation. The LED ring, through its density of elements and (at present) relative unfamiliarity to broader audiences as an interaction element, we see as a weak contribution to actionability. Taken as an ensemble, we hope the juxtaposition of complementary elements might (at least partially) resolve the screens false affordance, and yield a composite artifact that is more actionable than any of its constituent elements. Where we see

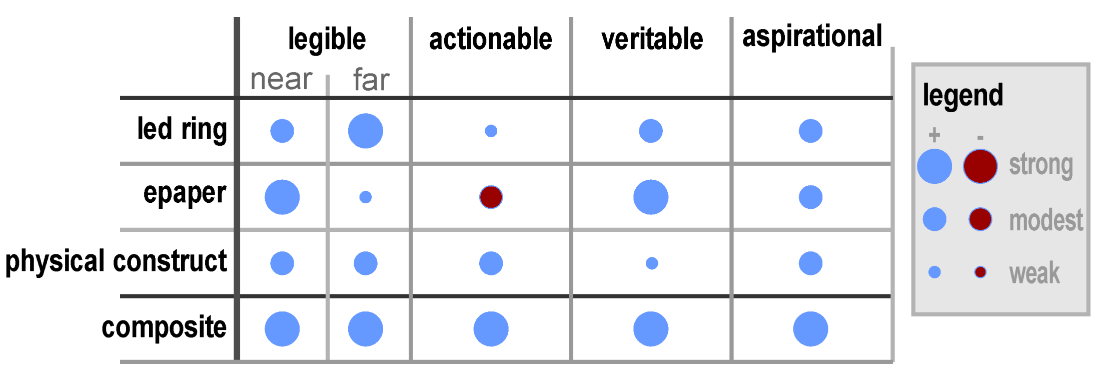


Figure 3.22: **LAVA engagements by active challenge coin elements.**

the epaper screen as the weakest element relative to “actionability,” we see it as the strongest in “veritability.” Especially when situated within a broader system context, the text allows for unambiguous identication of the intended virtual mapping. While “aspirational” is the most subjective facet, our hope is that a well-executed composite tangible, composed of an ensemble of potentially evocative elements (at least relative to present-day contexts), can yield an artifact that exceeds the potentials for impact of any of its individual constituent elements.

While the RGB Token and the Challenge Coins were both active devices, driven by microcontrollers and several input and output active components, we next explore hybrid devices.

In one definition, hybrid devices are those that embed components that usually remain inactive, being “awaken” only when in close proximity to an external source of power, such as the NFC tags of Hybrid Challenge Coins. In another definition, hybrid devices are those which incorporate some elements that are active, and some that are passive. We explore this approach with the Augmented Surface Dials.

3.12.2 Hybrid knobs

3.12.2.1 Augmented Surface Dial

One limitation of Microsoft Surface Dials is their ability to be tracked by the underlying multi-touch surface only when paired with Microsoft Surface Studio machines. When paired with other machines, the Microsoft Dial is not tracked, but can still be used off-screen.

Toward extending the ability of the Microsoft Surface Dial to be tracked on top on multiple multi-touch surfaces, I explored two approaches. The first approach is software-based. In this approach, the radius attribute of a touch point is analysed. If the radius is similar to the Microsoft Surface Dial (approx. 60 mm in diameter) the object is recognized as a Microsoft Surface Dial, and an interface element is centered beneath the Dial. While this is a simple approach, which may work with a number of development platforms (e.g. Unity 3D [21]), there are at least two main drawbacks: Not all displays are able to provide the radius of a touch point. The Unity 3D documentation for the Touch class warns that this attribute “works correctly on a limited set of devices” [62]. Another limitation is that this strategy does not allow for distinction between multiple Microsoft Surface Dials.

To overcome both limitations, I opted to encase the Microsoft Dial in a 3D printed structure.

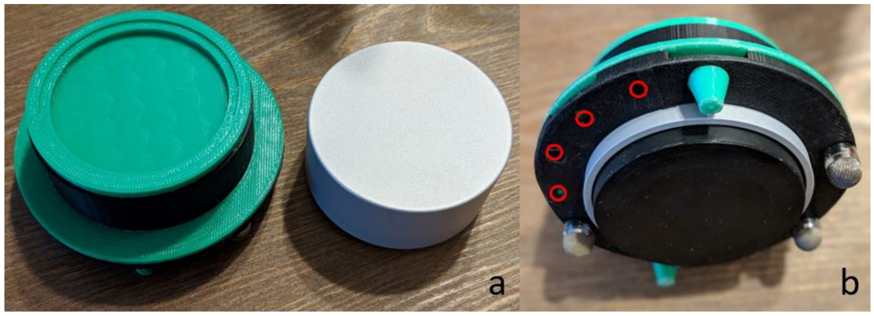


Figure 3.23: **Augmented Surface Dials.** *a) Augmented Surface Dial and Microsoft Surface Dial side-by-side. b) Bottom view of the Augmented Surface Dial. Touch pads can be arranged in several positions to assume five different IDs (positions are highlighted by red circles).*

The 3D printed structure become an outer-shell. At the bottom of this structure three touch points were added. With this approach, I am able to use the same algorithm that detects other tokens. However, the only attributes tracked is position and identification. Rotation is tracked by the existing mechanical rotary sensor of the Dial.

While I achieved the goal of tracking the Microsoft Surface Dial with commodity multi-touch screens, one last challenge remained. Similarly to the behavior of connecting multiple mice or keyboards, in the current implementation of the Microsoft Surface Dial it is not possible to distinguish the input from multiple Dials, a capability that is critical to implementing tangible user interfaces.

3.12.2.2 Individually Identifying Input from Multiple Augmented Microsoft Surface Dials

Initially, I searched for a solution within the Microsoft Surface Dial Api [20]. However, upon recognizing the absence of this feature, I searched several forums, and was able to locate a gitHub repository containing code for several Windows devices, including the Surface Dials [46]. This repository is curated by Microsoft developers, and upon posting a question on the forum, a senior Microsoft programmer confirmed my initial findings: no support for multiple Dials. The short question and answer can be found at `github.com/Microsoft/Windows-universal-samples/issues/751`.

To solve this problem, and connect multiple Dials to a single interface, I paired each Dial to a Windows based device (I used multiple tablets for portability). Each tablet relayed rotational information, button clicks and its id to the host system running the tangible interface. Communication was achieved via OSC messages exchanged between each Dial host (tablets) and the interface host. This allowed for low latency, and perceived real-time interactions with the Microsoft Dials and our tangible interfaces. This approach combined with the three touch point identification of each Dial, allowed us to create interfaces in which multiple Microsoft Surface Dials could operate concurrently. Fig. 3.24 presents a diagram of the hardware and software architecture implemented.

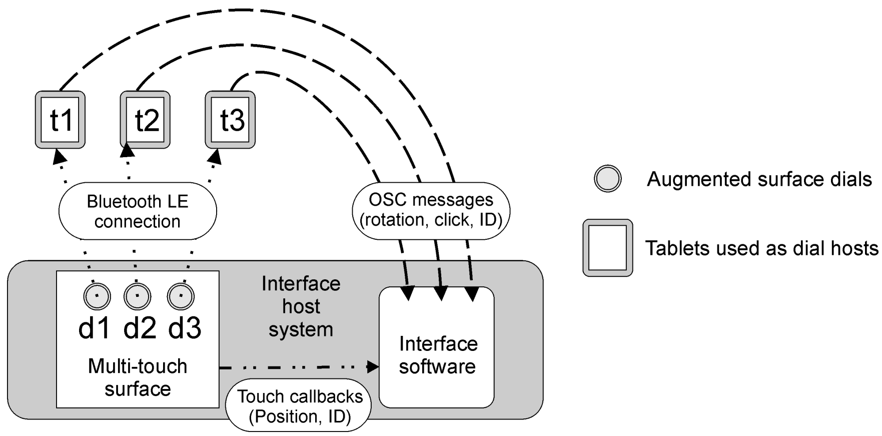


Figure 3.24: **Architecture to individually identify multiple augmented surface dials.** *Each augmented surface dial is paired to a dial host via Bluetooth LE. Tablets may be used as dial hosts. Rotation, button clicks, and IDs are sent by the dial hosts to the interface host via OSC messages. Position is obtained via touch callbacks generated by the touch points in the augmented surface dials. By merging the information from the sources, each Microsoft Dial can be identified, together with individual button clicks, and rotational interaction.*

3.12.2.3 Hybrid Challenge Coin

Having explored variations on active and passive dials, we decided to explore devices that would rely on capacitive pads for position and id, but would also embed NFC tags [209] as hybrid elements.

Several opportunities and challenges emerge when creating such devices. One major limitation of capacitively sensed dials for commodity multi-touch screens based on constellations of three touch-points is the limited number of distinct ids that can be recognized. In our previous work, we found that up to 8 ids usually work reliably, with some multi-touch surfaces being able to recognize up to 16 ids (e.g. Microsoft Surface Studio desktop machines). By combining our previous capacitive sensing strategy with embedded NFC tags – by associating (e.g.) each token to a unique

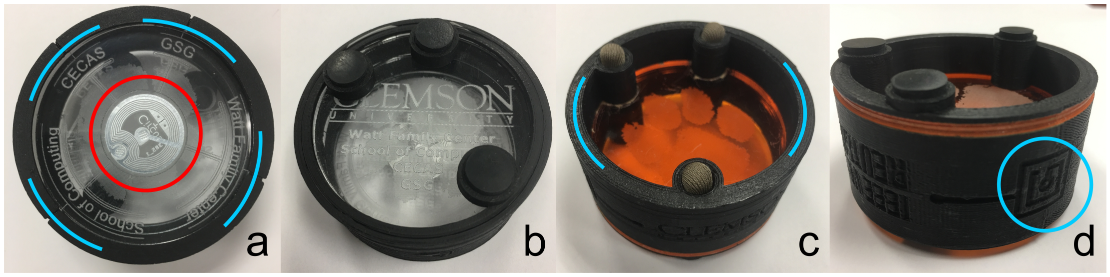


Figure 3.25: **NFC hybrid tokens.** *a) and b) Top and bootom of 5-tag nfc token. This token celebrates the school of computing, the Watt family center, the graduate student government, and the college of engineering computing and applied sciences. Each nfc tag on the side of the coin (highlighted in blue) links to a webpage at Clemson university. The top NFC tag (red circle) links to a webpage relevant to the recipient of the token. c and d) Top and bottom of a 2-tag NFC token. This token was part of, and celebrated, a tutorial presented by me at the 2018 IEEE VR conference on how to combine tangibles and virtual reality.*

ID contained on the NFC tag, – in theory the number of unique tokens interacting with a system can be expanded to hundreds, thousands, millions, and beyond, albeit still with a limited number of concurrent on-screen tokens.

Embedding NFC tags into 3D printed artifacts

Inspired by our approach to embed acrylic discs inside tokens, I devised a similar approach to embed NFC tags. This time, I designed the walls of the knobs to be composed of two concentric cylinders, with empty space (approx. 1 mm) between them. During printing, the process is stopped at a desired height, and one or more NFC tags can be inserted in the empty space inside the walls. Upon printing the top layers of the knob, the gap between the two concentric rings forming the walls is closed, forming a single body. Using this approach, I was able to embed up to 6 NFC tags along the walls, considering a knob of approx. 60 mm in diameter.

Figure 3.25 shows two versions of our hybrid knobs. The first (Fig. 3.25a and b) contains three layers of acrylic, four NFC tags embedded in its walls, and one at the top. The bottom has a constellation of three touch-points with conductive rubber pads. The second token (Fig. 3.25c and d) shows a second version, with two NFC tags embedded in the walls, and a single acrylic piece in the middle of the body. This token has patterns of three touch-points on each side; one made of conductive rubber pads, and the other made of metallic fiber stylus tips. This version was presented and utilized (in conjunction with a smartphone-based interface) during a 3-hour tutorial presentation at the 2018 IEEE VR conference, described in detail in section 5.7.

LAVA mediation engagements

One objective of these tangibles is explore hybrid approaches to extend the capabilities of (passive) dials, once again, into composites that exceed the capacities of any approximation taken individually. Embedding the NFC tags provided opportunities to explore a number of facets of the LAVA heuristics. Figure 3.26 explores these perspectives. The rows compare the passive bodies of the tokens, NFC elements, and their composites. The columns depict the facets of LAVA. "Legibility" is contemplated from two mediation perspectives: legibility by humans and by machines. I regard the passive bodies of hybrid knobs as moderately legible by both. By humans through textual and iconic images on the acrylic pieces, as well as in the 3D printed bodies (e.g. indicating the position of embedded tags). They are also legible by machines, by means of the three touch-point patterns. As discussed previously, I don't claim high scores for this type of machine legibility; limitations in the number of concurrent ids, and precision were, in fact, some of the reasons for working toward hybrid artifacts. In essence, the three touch-point pattern is limited in the data it can describe, and there the information it can communicate to the underlying tangible system (hence giving it a moderate score). NFC tags are not legible by humans (beyond recognition of existence), but they are (strongly) legible by machines. They may contain (currently) kilobytes of data, which may represent higher levels of information (e.g. web links), therefore, they receive a score of being strongly legible by machines. These two approaches, therefore, complement each other.

The form and shape of the coins communicate their affordance of rotation, and I consider them as moderately actionable. On the other hand, as of now, NFC tags and readers are restricted in availability and popularity, albeit this may progressively change as they become integral components of a number of popular devices (e.g. smart phones). I consider both to be moderately aspirational in their form and appearance. Especial attention in to this facet was given by employing "transparent"

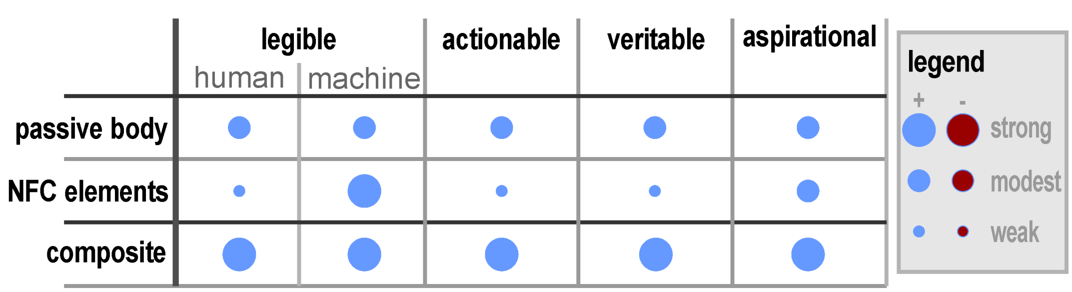


Figure 3.26: **LAVA engagements by hybrid challenge coins.**

NFC tags at the top of one of the hybrid tokens (Fig. 3.25a).

3.13 Discussion

The hardware and software approaches described in this chapter, and applied to a number of efforts described in the following chapters, have shown to be effective in supporting tangible user interfaces in combination with commercially available commodity multi-touch devices, and physical artifacts that are either laser cut, 3D printed, or a combination of both. However, I do not claim that the performance obtained is in every case superior to special purpose hardware, or that this approach works with any device. A number of aspects may reduce the effectiveness of commercially available commodity devices as platforms for tangible user interfaces. Multi-touch surfaces found in main stream commodity devices are usually calibrated to achieve best results when operated by human fingers. While they are also calibrated to work with stylus tips, the usual use-case scenario hardly considers the use of three concurrent stylus-tips simultaneously (or more), as is the case with the dials and tokens developed. Some implications are that dials may not always work as desired, and most multi-touch surfaces support only up to 10 touch points, limiting our maximum number of concurrent tokens on-screen to three. Also, the top layer of the multi-touch surface may interfere with the performance of the dials. Usually, the best performance is achieved when the top layer is glass, and not plastic. The implemented system is also limited to capacitive-based sensing, and will not work on a large variety of displays that employ infrared sensors, including some that are considered low cost and adapt a infrared sensor to existing 40, 55 or 60-inch TVs [22].

3.13.1 Human and Computer Legibility

The LAVA heuristics – **L**egible, **A**ctionable, **V**eritable, and **A**spirational – provide a conceptual tool for regarding different aspects of representation and control within interaction design in general, and tangibles in particular [261]. The "L" in LAVA, is concerned with the extent to which the tangibles are expressed in physical and visual representational forms that allow users to read them. Considering this heuristics, most of the tangibles developed contain elements purposefully design to provide human legibility. (fig. 3.21 and 3.25).

I extended the notion of user legibility, to the notion of computer legibility. One form of computer legibility that was widely explored is sensing of tangibles by capacitive sensing of spatially multiplexed touch points. However, I have enabled the tokens to support other means on sensing or computer legibility, for example computer vision. One instance is the token shown on Fig. 3.25c. The top of the token is decorated with an icon that could be identified by a computer vision system. More interesting still, that icon could describe a QR code, and provide additional, albeit static, information to the interface system. Another example is shown in Fig. 3.21. The Active Challenge Coin's electronic paper displays allow for both human and computer dynamic readability. Here, QR codes could also be utilized to convey information to the interface system, with the advantage of being able to convey dynamic information. Arguably, another form of computer legibility is achieved by the use of NFC tags in the Hybrid tokens.

3.13.2 Toward an Ecology of Interoperable Tangibles

Multiple sensing approaches, human and computer legibility embodied by some of the tokens point at exciting possible futures for tangible interfaces. While it is currently hardly desirable for a single, isolated system to employ multiple sensing strategies for the same type of tangibles, we can begin to imagine a constellation of systems (dozens, hundreds, thousands, and beyond) which employ and recognize a variety of interoperable tangibles; some capacitively sensed, some sensed by computer vision, some enhanced with static information, others with dynamic information.

In this context, tangibles, especially general purpose ones, have the potential to be conceived not to be associated to a single system, and shared by multiple users, but to interoperate among several existing systems, and prospectively be "owned" by a single user. Several implications may rise from this envisioned ecosystem of tangibles. It may be desirable from a hygiene standpoint to own a set of tangibles, instead of sharing with others. People may have the opportunity to express themselves through their tokens, the same way they do with clothes, and other objects they carry; Cellphone cases are often stylistic statements first, and protection apparatus second.

Figure 3.27 summarizes the tangibles created, comparing several attributes that characterize them in tabular form. In the next chapters I explore some of the dials described here in the context of systems that combine tangible interaction (sometimes with knobs, sometimes with artifacts of diverse forms and scales), and other forms of mediation and interaction.

	RGB Token	Active Challenge Coin	Hybrid Challenge Coin	Augmented Surface Dial
Requires Power	Yes	Yes	No	Yes
Token Labeling	Active (RGB LED Ring)	Active (RGB LED Ring, and 2-inch e-ink display)	Passive	Passive
Identification	Active	Passive (capacitive, three-point pattern)	Passive (capacitive, three-point pattern)	*Non-Microsoft Surface Machines:* Passive (capacitive, three-point pattern) *Microsoft Surface Machines:* Active
Position Tracking	Active (color sensor)	Passive (capacitive, three-point pattern)	Passive (capacitive, three-point pattern)	*Non-Microsoft Surface Machines:* Passive (capacitive, three-point pattern) *Microsoft Surface Machines:* Active
Orientation Tracking	Active (Magnetometer)	Passive (capacitive, three-point pattern)	Passive (capacitive, three-point pattern)	Active
Connection	Bluetooth	Wifi	NFC Tags	Bluetooth LE
Communication Protocol	OSC messages, simplified TUIO protocol	HTML + REST api, or OSC messages, and simplified TUIO protocol	NFC protocol	HID protocol
Embedded Sensors	Color, proximity, magnetometer, accelerometer, button click	None	None	Button click
Other Components	LED ring, and buzzer	LED ring, e-ink display	None	None

Figure 3.27: **Properties of the classes of active and hybrid tokens created.** *Some tokens have active labels for legibility, others passive. The tokens also combine active and passive tracking and identification strategies. Connection and communication is achieved with several different protocols.*

Chapter 4

Combining Interaction Modalities: Multi-touch and Tangible Interaction

> *"We didn't build the interstate system to connect New York to Los Angeles because the West Coast was a priority. No, we webbed the highways so people can go to multiple places and invent ways of doing things not thought of by the persons building the roads."*
> *Neil deGrasse Tyson*

As briefly discussed in the introduction, research often focuses on tangible interfaces acting by themselves, or tangible interfaces in comparison with "competing" interaction techniques within the tangible interaction field. However, when considering "mainstream" interaction paradigms, hybrid approaches are often the norm. With several examples ranging from operating systems which combine both graphical user interfaces and textual/command-line interfaces, to smart-phone platforms which blend multi-touch with traditional applications, such as web browsers.

This chapter describes the work toward combining two interaction modalities: multi-touch and tangible interaction in the context of computationally-mediated scientific posters. I start by describing three sample applications, which form the technical and conceptual foundation for the more complex platforms developed later.

4.1 Preliminary Work

All three sample applications grew out of the development of laser cut knobs, and were aimed at developing the software capabilities necessary to develop later work. Such capabilities include *detection*, *identification* and *sense of rotation* of individual knobs in combination with appropriate user feedback. Two of the three increasingly complex applications developed expect some actions to be performed with tangibles, and some with direct touch. Although the notion of combining interaction paradigms was not fully developed at the time, it later became the key concept of a manuscript published at the twelfth conference on Tangible, Embedded and Embodied Interactions (TEI) 2018. All three applications are based on Python-Kivy natural user interface libraries (`kivy.org`), an open source Python library for rapid development of multi-touch applications.

4.1.1 Sample Applications

The sample applications were developed to demonstrate a number scenarios where the tangible knobs can be applied. Two of them (Matching Blocks and Collage) add to the large group of TUI applications designed for children [298], the last (VideoPlayer) is directed at adult audiences. All three applications have been tested on a number of devices: Microsoft Surface Pro tablets, a Lenovo laptop with capacitive multi-touch screen, and a 27-inch Dell capacitive screen connected to a desktop.

4.1.1.1 Matching Blocks

The sample application depicted in Fig. xx is inspired by children's toys that require fitting objects, e.g. blocks of wood of different shapes into corresponding slots. In the Matching Blocks application, the goal is to match the geometric figure on the top of the knob with the same figure on the screen. If the knob is placed inside the square that contains the figure that matches the knob, a green check-mark appears on the lower right portion of that detection area, followed by a sound that indicates the correct matching. If the knob placed has the wrong geometric figure, a red "X" appears, and a sound indicating an incorrect match is played. Six knobs are needed to play the game.

To distinguish one token from another, I created face plates made of soft wood, engraved with distinct shapes, in reference to the classic wooden toys that inspired this application. The upper and lower pieces of the knobs' bodies are made of acrylic of a variety of colors, in an attempt to appeal to children's eyes. I employed a cut-away strategy to make the geometric shapes on the face plates appear in different colors. We also designed the shapes on the screen to match the color of the shapes on each knob, allowing for the matching of both, shape and color.

As a proof of concept, the Matching Blocks application successfully achieved its goal. Detection and identification of six distinct knobs was performed precisely, paving the way for more complex programs to be developed.

Figure 4.1: **Matching Blocks sample application.** *a) One of six Matching Blocks knobs with wooden face-plate. b) Matching Blocks interface after the triangle knob has been correctly matched with its slot. d) Matching Blocks interface with all six knobs. Note the circle knob has been place in the incorrect spot.*

4.1.1.2 Collage

The Collage application works as a set of *stamps* for creating compositions, or *collages* (Fig. xx). Each on-screen element is represented by a distinct knob. Users are free to *stamp* the elements anywhere on the screen, and as many times as desired. When the program starts, a blank screen is shown. The user proceeds to select a background, and to add different elements to the scene, such as a house, a dog, trees, or apples to create unique compositions. This application was inspired by the Token Presence application developed in [92]. Besides employing capacitive knobs, Collage differs by allowing multiple copies of the same image to be created, and remain on screen after knobs are removed. In Token Presence, they appear only while the token is placed on specific mapped areas, and disappear when removed.

One goal of this application was to apply a larger number of knobs than the Matching Blocks App. In total, 12 knobs can be detected and identified. While in the Matching Blocks application the tracking area of knobs was restricted to six squared regions, with Collage detection of any knob may occur anywhere on the screen. Every time a token is detected, the corresponding image is drawn on screen in the screen position relative to the center of the knob. Different knobs can be placed in the same spot, causing different images to overlap. I see this as a feature, since the user has freedom to create.

The tangibles in this application were inspired by rubber stamps. The bodies of rubber stamps are often made of wood; for this reason, the bodies of the knobs were made of balsa wood. With this choice, the knobs are slightly lighter than the acrylic ones, and users are often required to apply pressure onto the knobs for reliable detection. While this might be viewed as a problem in most use cases, it turned out to be a feature for our application. Users automatically associated the required pressured for detection with the pressure applied to stamps to produce "good" images, this added to the realism of this simulation. For the top face-plate, we chose a dual-tone acrylic material with an engraving of the screen element represented by each knob.

Besides incrementing the number of distinct knobs employed, this application also detected the angle of rotation of the knobs, allowing users to "stamp" objects in different angles. However, no parameter was manipulated by the rotation of knobs yet. Collage also implements a combination of tangible and multi-touch interaction. At any moment, each element on screen may be individually erased by entering the erasing mode. To erase a screen element, first the user performs a multi-touch action – click the "erasing mode" button on screen – then a tangible action, by placing the knob on top of the screen element to be erased.

Figure 4.2: **Collage sample application.** *a) Knobs being applied to create a scene with the Collage application. b) By touching the erase button use enters the erasing mode. c) User removing an apple from the scene.*

4.1.1.3 VideoPlayer

The VideoPlayer application presents a tangible user interface for selecting and playing videos. Knobs represent different videos, and are used to control playback. Users can play, stop, pause, seek, and control the volume of videos by placing knobs on specific control pads. Control pads float around the screen and can be moved freely with multi-touch actions. The video itself can also be moved around the screen and re-sized by finger touch. Since control pads and the video properties pad occupy considerable screen real estate, they can all be hidden at any moment by selecting a “hide” option.

This example expands position and angle detection to parametrically controlling program’s attributes with (tangible and/or multi-touch) rotational controls. We explore rotation to select discrete and continuous variables. By placing and turning a knob that controls reproduction, the user can choose to play, pause, and stop a video. This is an example of a discrete variable. The volume knob represents a continuous variable. Turning the knob increases or decreases the volume. Each control pad can be controlled by touching the pads with two fingers, or by a placing the correct knob on top of the pad. In another example of multi-touch interaction, detection areas can be moved around the screen using finger touches, but not by knobs.

Two types of customization have been considered for the VideoPlayer. Knobs representing movies have been customized to be colorful, and carry the name of the videos they represent. Knobs representing controls have been given a more generic look as the handles in Fitzmaurice’s Graspable User Interfaces [127]. I chose a transparent acrylic for the body of the knobs and a black dual-tone acrylic for the face-plates.

Figure 4.3: **VideoPlayer sample application.** *a) Video container knob being used to load a video. b) Control knob being used to play a video. c) Multi-touch actions can be used to move on-screen elements, and re-size videos.*

4.1.2 Cardinalities between Digital Controls and Physical Knobs

The sample applications demonstrate some of the possible cardinalities between digital control pads and knobs. There is a one-to-one relationship between the digital control pads displaying geometric shapes, and the physical knobs in the Matching Blocks application. The Collage application shows a one-to-many relationship between the scene background, and the knobs representing rubber stamps. The VideoPlayer application demonstrates both a one-to-one relationship for the volume and seek knobs, and control pads, and a one-to-many relationship between the video selector pad, and the knobs representing videos.

While these relationships do not seem to help the designer of isolated tangible user interfaces beyond understanding, and designing single- or multi-user interaction, this analysis seems relevant when considering ecologies of interoperating applications that may be based on tangibles that belong to users, instead of belonging to a specific system. In this hypothetical scenario, every tangible interaction would have to consider many-to-may relationships, since several (presumably multi-purpose tangibles) would have to interact of several, if not all on-screen interactors.

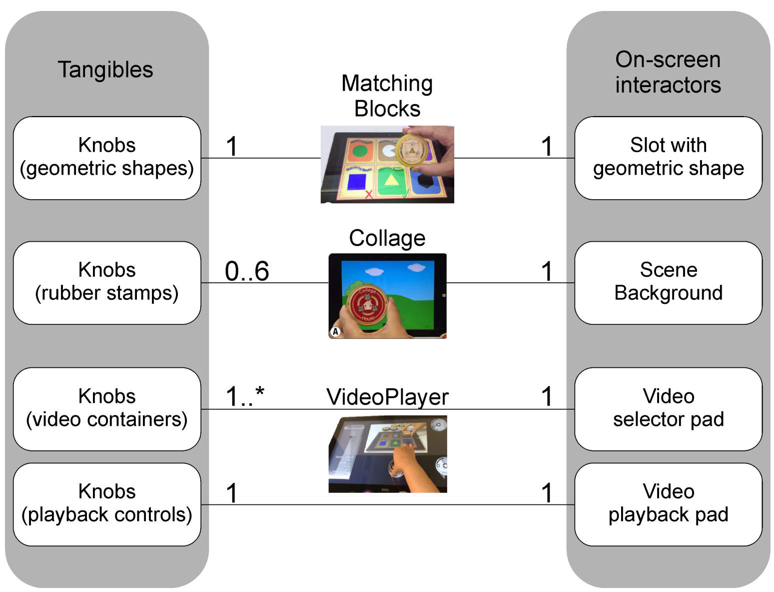


Figure 4.4: **Cardinality between tangible knobs and screen interactors.**

ask if code, and additional digital content should be added uploaded to the internet.

4.2 Combining Tangible and Multi-touch Interaction

Building upon the conceptual and technical knowledge of the three applications described, I focus on two platforms specifically developed to explore the legibility and actionability associated with systems that support tangible and multi-touch interaction in scientific poster scenarios.

I propose systems that offer functionality *with* and *without* physical tangibles[1] and *with* and *without* virtual/"soft" interactors, including combinations of both. I regard "pure-multitouch" and "pure-tangible" variants, as well as hybrids thereof, all as "first-class citizens." In what I and others consider as a cyberphysical interface (CPI) – a system designed to integrate support for both physical and virtual interaction modalities.

Here, I describe systems that implement computationally-mediated scientific posters, leveraging on the existence of several communities of content generators that are engaged in various areas of research. I developed two platforms. Poster developers were alternatively asked to adapt their content to the constraints of a tightly-coupled platform, or offered basic building blocks (e.g., methods to identify tangibles on a multi-touch screen) with more freedom to design and build their own interactive presentations. In the next sections, I describe posters developed for these two groups of interfaces by undergraduate students, discuss interaction aspects, and explore lessons and challenges from the posters created.

One contribution of this work is the addition of computationally-mediated scientific posters to the growing number of domains toward which tangible interaction approaches have been employed. More broadly, I contribute by exploring novel combinations of physical and virtual interactors which I expect can generalize beyond my own examples. Last, I enhance poster presentations (with these systems) by employing tangible interfaces toward promoting collaboration and learning experiences [237].

[1] tangible interfaces' physical interactors of tangible interfaces are often called *tangibles* [242].

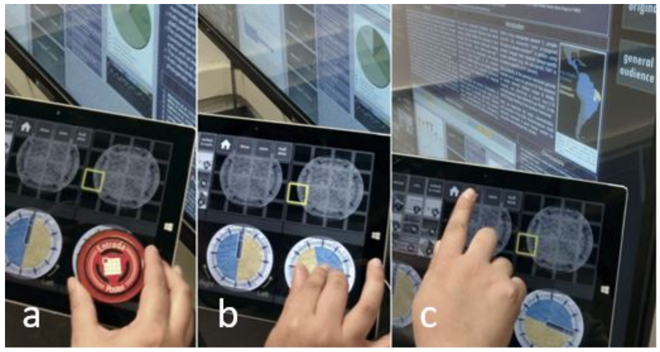


Figure 4.5: **Interface combining hard, soft, and multi-touch interaction.** *Actions can be performed with a) tangibles, b) by interacting with soft tangibles, c) and by interacting with "traditional" interface widgets (e.g. buttons).*

4.3 Scientific Poster Context

Paper posters – whether used for (e.g.) advertising movies, food, health and political campaigns, or scientific results – have long been widely deployed. In some respects, posters are not an obvious low-lying fruit for tangible interaction. That said, I found them an intriguing and promising target for a number of reasons.

First, both in educational and professional (e.g., conference) contexts, the production and sharing of posters is very common. Posters are a proven tool for conveying knowledge quickly, with visual communication as a key facet. Within the universities where this work has been developed, more than a hundred undergraduate students each summer are required to produce scientific posters communicating their research. While advertising and informational displays have increasingly migrated to digital signage, educational and conference posters have remained mostly paper-bound. With the advent of large, high resolution (esp. 4K), relatively inexpensive displays, increasing engagement by academic posters with digital displays seems not a question of "if," but "when" and "how."

Others and I [112, 231] see this as driven not only by technological availability, but also by opportunities for interaction. Broadly viewed, the visual real estate of academic posters can be divided into blocks of text and figures. Still figures invite dynamic (e.g., video and animation) and interactive content. Text blocks also seem promising for interactivity. One variation might be hyperlinkage – whether to greater depth (e.g., cited literature) or breadth (e.g., Wikipedia articles and YouTube videos providing background concepts and context). Another might be tailoring text for different audiences: e.g., for faculty experts vs. the general public.

One avenue for such interactivity is direct touch interaction with a digital poster display itself. This has the benefit of greatest consistency with traditional posters, and some level of "compactness," especially when mindful of present contexts where hundreds or thousands of traditional-scale physical posters are simultaneously presented [231, 205]. Direct interaction also brings a number of trade-offs. While this will likely change, poster-scale (e.g., >=55"/140cm diagonal) displays supporting multi-touch input are presently on the order of 10x more expensive than display-only units.

An alternative or complement for direct touch interaction is indirect interaction. One such variant is with digital tablets or other devices that display complementary meta-information. Another is with tangibles. During poster presentations, whether a presenter is present or not, tangibles might offer implicit "invitations to interaction, " or even "interaction takeaways" (i.e., artifacts that can be brought away by visitors following an interaction). They can also facilitate the transfer of control between presenter and one or more audience members. If horizontal tablet or tabletop displays are used, tangibles can provide kinesthetic awareness for navigating in eyes-busy situations (whether gaze is toward the vertical display or audience members).

4.4 Mixing Multi-touch and Tangible Interaction

As mentioned earlier, a key aspect of the cyberphysical interface (CPI) approach for posters is support for interaction with and without physical tangibles, and with and without virtual/"soft" interaction elements. Figure 4.5 shows one of the interfaces created, which affords interaction with hard, and soft tangibles, and multi-touch interaction with more "traditional" interface elements (e.g. buttons). Several examples are illustrative. For text entry with contemporary tablet computers and smart-phones, an ubiquitous feature is support for both virtual keyboards, and (when available) physical keyboards. We understand neither is in all respects "better." Physical keyboards allow eyes-free operation, liberated screen real estate, and (supported by tactility) generally greater speed; while virtual keyboards can greatly lessen a mobile user's "baggage" [99].

I see a similar prospect, extended to many aspects of previously "pure-tangible" interfaces, as holding potential for greatly increasing their use and deployment. Perhaps the strongest example of which I am aware is the ReacTable [156] and ReacTable Mobile [15, 16, 53] family of music interfaces. The ReacTable is one of the best-known tangible interfaces of the last decade, while ReacTable Mobile is a purely virtual (multi-touch based) version. As with virtual/physical keyboards, the two variations are marked by trade-offs between screen and physical real estate, eyes-busy and kinesthetic performance, mobility, and cost. In a similar spirit, the hybrid poster-related interfaces are designed with the capacity to receive physical/"hard" input (e.g., with physical, dial-like tangibles), and the capacity to receive input from on-screen elements (e.g., via button press or virtual/"soft" tangible interaction), with the choice of interaction modality varying by user, time, and context. In the presence of good design [213], such systems could leverage the complementary benefits of physical and virtual interaction modalities, and allow flexibility to accommodate contextual and preferential differences (including varying availability of enabling hardware).

Before presenting the grounding prototypes my collaborating poster creators and I have developed, I first introduce the concept of "soft" (virtual) tangibles. This is followed by a description of "hard" (physical) tangibles, and their physical forms.

4.5 Soft Tangibles

Initially, my focus was upon combined interaction of physical dials and "traditional" on-screen multi-touch input elements (e.g. buttons). Later, we noticed the opportunity for direct finger-touch interaction with on-screen representations of tangibles, without requiring the use of physical/hard tangibles. We refer to these as *soft tangibles* (Figure 4.5b).

Others have considered non-physical elements in tangible interaction. Ullmer et al. [256] focused on physical constraints, but also suggested constraints in dynamic graphical form. Variations blending the use of physical objects and finger-touch have also been explored. Wobbrock et al. [290] and Kammer et al. [160] explored touch gestures for interactions with surfaces. Angelini et al. [81] considered holding an object and touching it as two different components of interaction. Here, gestures with tangibles were decomposed into move, hold, and touch elements, and a taxonomy considering the possible combinations was defined. Mazalek et al. [189] considered gestural interaction with active tangibles and multi-touch elements as a promising approach for exploring Big Data. Morales et al. [198] explored finger-touch to define patterns (by constraining the users' grasp) on capacitive touch-screens, allowing users to interact with on-screen elements.

I see considerations for soft tangible interaction as likely to be beneficial when combined with "traditional" on-screen elements and physical tangibles. I envision systems employing a dynamically evolving mixture of hard and soft tokens (here, dials) and constraints [256, 245]. Similar to the way contemporary web search engines fuse a mixture of typed and predictive/suggestive text [140], physical dials might be intermingled with soft predictive/suggestive dials.

4.6 Hard Tangibles

A number of research [95, 98, 269] and commercial systems [13, 3] have employed partially conductive tangibles on capacitive multi-touch surfaces. Along similar lines, our design of passive capacitive-sensed knobs incorporates constellations of three touch points, as described in section 3.7.1. The bodies of the hard tangibles were built with laser cut technology alone, or combinations of laser cut and 3D printed strategies, both approaches were discussed in sections 3.9 and 3.11.

In the next sections I present two platforms that mix interaction with hard and soft tangibles on capacitive surfaces. First, I present a tightly structured platform; then, a less constrained approach; followed by prototypes created by two separate cohorts of undergraduate students.

To explore the concepts I propose, I sought a domain that would engage undergraduate students and the broader public, particularly as relating to science, using platforms that would allow immediate and progressively broadening deployments. I found interaction support for the creation, presentation, and engagement with computationally-mediated research posters to fit well these constraints. These motivated the development of the *Entrada* and the *Knob-tray* platforms.

4.7 Entrada Platform

The Entrada platform, depicted in Figure 4.6, replaces paper posters with screen-based computationally-mediated systems. A full-size poster can be displayed by a vertical screen (in our case, 55-60 inch diagonal and 3840 X 2160/4k pixels resolution). Microsoft Surface 3 tablets control all aspects of the posters (e.g. selecting content, zooming, manipulating 3D models) with an interface that allows interaction by touch, and by hard and soft tangibles. The tablet interface, is composed of a 3 by 2 grid, with buttons at the top, and *soft* tangibles for rotational interaction with finger-touch

Figure 4.6: **Computationally-mediated poster platform Entrada.** *a) Entrada interface with one or more large vertical screens, and tablets to control interaction. b) Detail of the Entrada tablet interface. c and d) Students presenting at the 2017 NSF REU program with the Entrada platform.*

or with *hard* tangibles at the bottom (Figure 4.6b).

The tablet interface was tightly structured, model-based, and automatically generated, with implementation details managed by system developers (as opposed to poster content creators) [201]. Poster creators define associations between buttons and content for the vertical display. The tablet interface automatically imports these associations, generating the tablet's on-screen elements. The advantage is that users, even without any interface design experience, can implement their posters and rely on the tablet's software to create high-quality interfaces that combine multi-touch with hard and soft tangible interactions. A trade-off is that fewer opportunities for customization are available.

4.8 Knob-Tray Platform

In contrast to the Entrada platform, the knob-tray platform gives poster creators more freedom to create the posters, at the cost of more per-poster software development and less between-poster interaction consistency. Here, the platform provides basic interface building-blocks, without any automatically generated elements constraining the design. Poster creators can choose among several display configurations. Options include a single vertical screen, a single horizontal screen, two screens (one horizontal and one vertical), or pairs of horizontal or vertical screens; all supporting multi-touch and tangible interaction. The basic building-blocks provided for the prototypes developed were:

Soft tangible component: I provided poster creators with a class for the implementation of soft tangible objects. These objects could be easily customized and were capable of identifying our 3D printed or laser cut knobs;

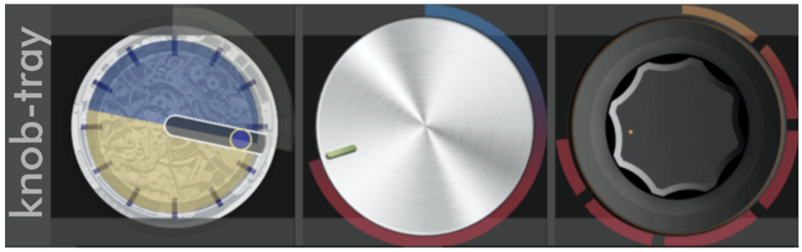


Figure 4.7: **Sample knobs offered with the Knob-tray platform.** *Multiple configurable knobs and a library of code samples are offered with this platform. Content creators are responsible for creating interactive posters based on the code samples that can be widely customized.*

Physical knobs: Eight distinct 3D-printed knobs were provided. Users could also opt to design and 3D print their own knobs;

Tray component: Users had the option to use stand-alone soft tangibles or configure a tray with multiple knobs. Trays made it easier for developers to position multiple knobs within their screen layouts (Figure 4.7); and

Code samples: A set of sample software code was made available to assist users as they began to develop with the knob-tray platform.

Both platforms were developed with the Python [19] Kivy library [267]. Two-way communication is handled by OSC [293] messages exchanged between devices controlling and rendering content. Messages are based on a simplified version of the TUIO protocol [159].

4.9 Creating Posters with the Platforms

In June and July of 2016, the Louisiana State University held the 7th NSF REU (Research Experience for Undergraduates) program [27]. As with many of the approx. 700 nationally funded REU programs, all participants were required to create paper-posters by the end of the program to show their research accomplishments. During this edition, REU participants were invited to volunteer to create computationally-mediated posters using the Entrada platform, in addition to paper-posters. Twelve students volunteered. Due to our limited ability to support the students, five were selected to participate in ten workshop sessions (A sixth student joined in the final week, without participating in the workshop sessions.) The workshops were designed to help them create content and design the posters, while providing us with feedback.

Following the experience developing the Entrada platform, during the Spring semester of 2017, 19 undergraduate students, divided into six groups, created computationally-mediated posters with the knob-tray platform. This time, the creation of the posters was part of the requirements for the Tangible Embedded Interaction (TEI) course offered at Clemson University. The course was mainly attended by senior-year students, and did not require specific programming skills. Each group was asked to select a topic engaging research groups at the university and to create a poster presenting that research. Students were also asked to seek user-experience and usability feedback from the members of the research groups they picked, and from other potential users. Next, we describe several example posters created with both platforms.

4.9.1 Poster 1: Additive manufacturing of dial-like tangibles

Figure 4.6c depicts a poster developed with the Entrada platform being presented by an NSF REU student. This poster displayed information about the fabrication of tangible knobs using 3D printing techniques. Some of the knobs presented were similar to those employed in the operation of other Entrada posters. The student prepared his interactive poster presentation to utilize tangible knobs, while also explaining how they had been fabricated. The tangibles served as tools to operate the posters, and most importantly, as points of attraction and promoters of engagement. Viewers were interested in holding the knobs and trying them on the tablets. They often asked questions about both the hardware (the tokens themselves) and the software (running the poster). Soft tangible interactions were also employed, especially when physical knobs were not available (e.g. after handing knobs to viewers).

This poster was awarded one of two awards given to all paper and digital posters, and was invited to represent Louisiana State University at the national REU Symposium.

4.9.2 Poster 2: Gravitational waves

The second poster developed with the Entrada platform was about the detection of gravitational waves in the context of the Laser Interferometer Gravitational Wave Observatory (LIGO) [76]. The student chose not to emphasize the use of knobs, instead focusing on implementation of content and text for different target groups. Most of the interaction occurred either via button-press or rotation of soft dials with fingers. Although not employing tangibles, this poster gathered sub-

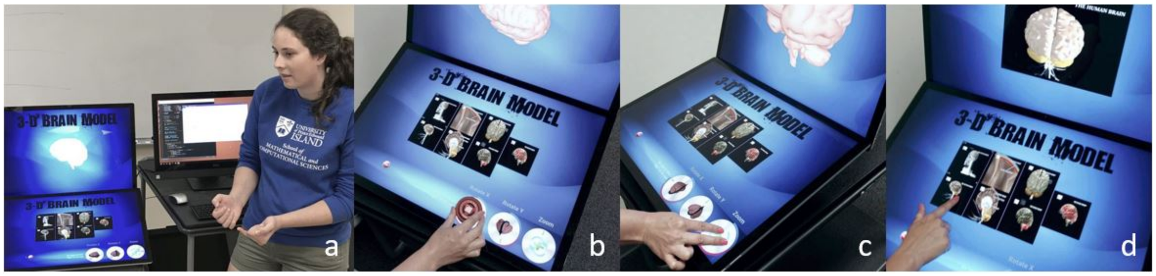


Figure 4.8: **Brain-model poster.** *a) Student giving a classroom presentation of her poster; b) Student controls zoom and rotation of the 3D model with soft tangibles; and d) Student touches the tiles to select a video.*

stantial attention from viewers. It employed a variety of animations and short clips to explain the gravitational waves phenomenon, a concept that would most likely be challenging to present with a (static) paper-poster. Regarding interaction, buttons were usually employed to change discrete parameters (e.g. selecting slides), while soft-tangibles were mostly used for controlling continuous parameters, such as zooming images.

4.9.3 Poster 3: 3D brain-model

The 3D brain-model poster was created with the knob-tray platform (Figure 4.8). The poster was based on the work of a research group from Clemson University on 3D printing brain models replicated from human MRI scans. In contrast to the REU posters, this poster was designed to be a stand-alone system, without the presence of a stand-by presenter.

The development process adopted a user-centered iterative approach. The project began with pencil and digital storyboards, which were used as a visual basis for coding the program. Soft and hard tangibles were arranged on a knob tray. The first major project milestone was a rigid, but functioning, version. Once realized, the development team sought feedback from prospective users by showing demos to respondents and having them complete questionnaires.

By the end of March, a new version of the system was developed, and soon after, developers sought more extensive user feedback. Members of the research group and external undergraduate students from Clemson University were asked to interact with the poster's interface without guided instruction. Poster creators observed and recorded the interactions. The users were interviewed about the program and asked to complete a written follow-up survey.

The final version ran on two paired Microsoft Surface Studio machines; one used in vertical

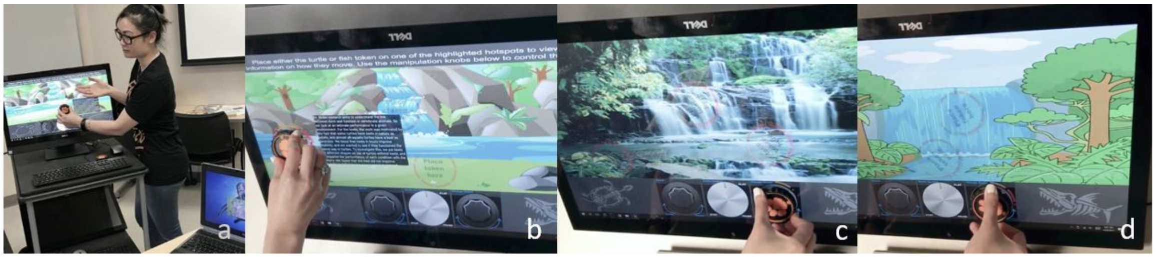


Figure 4.9: **Vertebrate biomechanics poster.** *a) Student demonstrating her poster during a classroom presentation; b) Student "dropping" a knob onto one of the hot-spots to display textual information; c and d) Student rotates a knob to chose among several habitats for one of the animals.*

orientation, and the other used in horizontal. The interface mixed pure finger-touch with hard and soft tangible interactions. The horizontal display worked as a control panel, featuring seven buttons, each bound to a specific video. 3D rotation of the brain could be controlled directly by touch on the vertical screen, and indirectly through the hard and soft dials on the horizontal screen.

4.9.4 Poster 4: Vertebrate biomechanics

Figure 4.9 depicts a vertebrate biomechanics poster. This poster was inspired by Clemson University's Creative Inquiry "Comparative Vertebrate Musculoskeletal Biomechanics" project. The poster displays information on research related to the movement of turtles and fish in their habitats. The interface consists of a single multi-touch vertical screen for content selection and display.

The tangibles envisioned for this project were 3D printed turtle and fish tokens, and a rotational parameter-control knob. For interaction, besides parameter-control rotation, students explored a variation on the "Pick-and-Drop" concept [221], in which users can pick up an object (i.e., the turtle token) and "drop" it onto the screen to display or manipulate content (at which point the virtual turtle could "swim free" from the physical token). During lectures, we emphasized the goal of allowing all actions to be performed in multiple ways (e.g. with tangibles and by touch). In practice, students did not always achieve this. Some actions strictly required the use of tangibles, such as selecting content by placing tokens on hot-spots. Other actions, such as video-playback functions, could be performed with hard tangibles, by finger-touch, or with soft tangibles.

During development, students sought feedback from four participants in two separate sessions of informal evaluation (two per session). Four iterations were developed based on the feedback. The final poster was visually appealing and viewers found the interaction to be exciting and enjoy-able.

The implementation of each poster taught lessons regarding how to combine multiple interaction modalities (e.g. multi-touch, hard and soft tangible interaction), how to create and implement computationally-mediated scientific posters, and how users interact with them. In the next section I briefly analyze how users chose the interaction modality. Then, I summarize observations and lessons learned during the development of the posters.

4.10 Interaction Modality Choice

With our platforms supporting hard and soft tangibles, as well as multi-touch elements, how do users choose among these modes of interaction? Interaction researchers in the multimodal interfaces field have long noted the criticality of context – e.g., user role, physical locale, parallel primary or secondary tasks, system properties – to modality selection [236, 276, 275]. We considered modality choice with our prototypes observing user role and physical locale.

User role: we regard users as in three classes: poster creators, presenters, and viewers,

Physical locale: Two locales have been identified: controlled environment and public setting.

With the Entrada platform, I observed students (as they interacted with the systems creating and presenting the posters) and viewers during the NSF REU poster session. Following the final poster presentation, students answered an 11-question Likert-scale questionnaire regarding usability factors of the Entrada platform and the effectiveness of their presentations. Students were also asked to comment on their overall impressions. With the knob-tray platform, students were observed during seven one-hour long development sessions, and three project presentations. By the end of the course, students were required to produce a written report including questionnaires applied during the development process of their prototypes. Next, I summarize the observations.

4.10.1 Entrada platform lessons

The uniformity of the tablet control-interfaces generated by the Entrada platform meant that poster creators adopted similar interaction strategies and modality-choices across the posters, and viewers could also leverage this familiarity.

While creating the posters, students tended to use buttons and soft tangibles. Hard tangibles were mainly used for testing purposes during short periods of time, independently of the activity performed (e.g. selecting content or zooming an image). Early in the development stage not many knobs were available, and students had to share them. We suspected that the small number of available knobs was one cause for their low adoption by the students. As research prototypes, the physical knobs had some performance quirks (e.g., sometimes requiring pressure to operate), which was also likely a factor hindering usage. Later, each student received several knobs (and more, upon request). We noted that the availability of knobs did not change the frequency or duration in which the knobs were used. Students still preferred soft tangibles and multi-touch interaction during the development phase.

When presenting the posters in a public setting, most students tended to use all three modes of interaction (hard, soft tangibles, and multi-touch interaction,) with choice depending on the action being performed. For selecting content (e.g. moving from one slide to the next), students tended to use the grid of buttons of the tablet interface. For selecting a function (e.g. zooming, translating), which involved navigating between multiple discrete choices, buttons were still most often used, but students also chose hard and soft tangibles to perform this task, frequently using the physical knobs. For performing an action involving a continuous variable (e.g. zooming in or out), hard and soft tangibles were used, with a tendency toward directly manipulating the soft tangibles.

The apparent contrasting behavior toward tangibles I observed between users in a controlled environment (while developing posters in the lab) and in a public setting (while presenting the posters) seems to be in agreement with observations by others. [102, 238] noted that tangibles tend to be chosen more often when multiple users are collaborating, and not chosen as often when working individually.

Besides the student who created poster 1, two other poster creators were particularly enthusiastic about employing tangibles in their presentations. Some design choices appear to have contributed to their enthusiasm. Both students opted to have two to three tokens, in addition to a token for controlling the poster, each linking to specific content. During presentation time, the tokens would be used to summon the content to be displayed. One student used the tokens as an integral part of his presentation, while the other used the tokens to display additional content only upon necessity, depending on the audience. In both cases, viewers and presenters seemed to enjoy the role of tokens as content containers, with the tokens embodying various facets of the topic presented.

Viewers of the Entrada posters had the opportunity to navigate them when the student presenters were not present. In this situation, viewers tended to emulate the interaction patterns of students. Upon learning that the use of hard+soft tangibles and multi-touch was supported for all functions, some viewers tried different variations. Many seemed curious about the tangibles and tried to use them even when they were not the expected choice (e.g. to select slides), indicating that some choices were driven by curiosity about the tangibles, not necessarily convenience or ease of use.

4.10.2 Knob-tray platform lessons

The knob-tray platform supports more diverse designs. Consequently, distinct interaction patterns were implemented by each group. Nevertheless, many similarities were observed between the prototypes created with the knob-tray platform, and the prototypes created with the more tightly-structured Entrada platform.

With the 3D Brain Model project, users preferred direct finger-touch (on the brain model or on the soft tangibles) to rotate the model on the 3D space. For zooming, users sometimes would pinch-and-zoom, and sometimes use the soft tangibles; few used the hard tangibles.

With the turtle project, the use of hard tangibles was required to select content. With a well executed, relatively intuitive design, users seemed to feel comfortable using the hard tangibles. For navigating video playback, as implemented, the use of the hard tangibles did not feel as natural, with soft tangibles being the preferred mode of interaction.

Similar to the Entrada platform, while performing as *developers in a controlled environment*, users tended to use buttons and soft tangibles instead of hard tangibles. Also similarly to the Entrada platform, while *in a public setting*, users tended to use all three modes of interaction, if available.

Poster viewers generally seemed more confused by the variety of possibilities and diverse designs of the knob-tray interfaces when compared to the Entrada platform. The more tightly-structured format of the tablet interface within the Entrada platform seemed more intuitive to users, although more limiting for developers.

4.11 Discussion

With poster 1, I observed that tangible knobs can enhance poster presentations by promoting viewer engagement, and that multi-touch, hard and soft tangible interaction can be effectively combined into a single experience. Viewers were curious and eager to touch and operate the interface with the tangibles, while the presenter fluidly chose between the interaction modalities available. With posters 4 and 5, I learned that tangibles can have a down side, sometimes distracting users and leading them to focus more on the tangibles themselves rather than the poster's main topic.

I also observed that tangibles seemed to enhance poster presentations only when the presentation was carefully designed to employ them and leverage their characteristics. Otherwise, users tended to ignore the hard tangibles and use touch (either to operate buttons or the soft tangibles). Without explicitly integrating tangibles or dynamic content into the presentation, I felt their presence did not intrinsically enhance the experience or attract the attention of viewers. In most cases I observed, employing tangibles clearly added to the poster presentation experience, attracting and engaging viewers. Nonetheless, the adoption of soft and hard tangibles by developers and users was not as high as first anticipated.

Reflecting upon the adoption of soft and hard tangibles, I noted two important challenges. First, in general, poster developers were familiar with multi-touch interfaces, and unfamiliar with (soft or hard) tangibles. I did not provide pre-existing posters to avoid unduly biasing content; but this initially left developers unclear how to integrate and allow users to interact with soft and hard tangibles. This may have contributed to more limited interface designs and, consequently, poor adoption of tangibles, especially with the knob-tray platform, which gave developers more freedom of design.

Second, our prototypes do not yet realize my envisionment of deeply integrated functional and visual interaction between soft and hard tangibles with "traditional" on-screen elements. The simple nature of the interactions employed may contribute to relatively modest use of hard and soft tangibles when compared to the (usual) multi-touch actions.

Figure 4.10: **ReacTable Live! tangibles [53]**. *The ReacTable Live! includes a set of twenty seven distinct tangibles.*

4.11.1 Analysing Reactable's Multi-touch, Hard, and Soft Tangible Editions

The Reactable [155] was described in section 3.2.2. While the company still commercializes the original ReacTable, currently "ReacTable Live!" [53], a number of other products have been released since the company's beginnings in the early 2000's. Together with ReacTable Live!, two other products are relevant in the context of cyberphysical systems: the ReacTable Mobile [54] and the ReacTable ROTOR [56].

One of the main goals toward defining the notion of CPIs is to implement, and investigate systems that can be interacted with purely by multi-touch, but realize their true potential when combined with other interaction modalities (e.g. tangible). Through the lenses of the CPI concept, ReacTable has realized three facets of CPI systems with its Live!, Mobile, and ROTOR line of products: purely tangible, purely multi-touch, and a system that embodies a combination of multi-touch and tangible interaction.

The ReacTable Live! is arguably one of the most successful commercially available examples of tangible user interfaces. Similar to my own approaches toward tangible interfaces, the ReacTable was "...designed to provide direct and intuitive interaction with sound through objects on a multi-touch enabled screen." [53]. Interaction is mainly driven by twenty seven distinct tangibles (Fig. 4.11). Some of them have on-screen modifiers, which can be accessed by touch.

While the ReacTable Live! is primary a tangible user interface, the ReacTable Mobile is primarily a mobile multi-touch application. Similarly to the tangible-based system, the mobile edition expects gestures and touches to be performed, often with both hands. Unconstrained by the physical nature of hard tangibles, this version gives users the possibility to add a number of new (soft) objects to their collections, providing the ability to create more complex and creative musical pieces.

In the context of combining multiple interaction modalities, perhaps the most exciting edition in this family of musical interfaces is the ReacTable ROTOR. In line with my own vision and approach for cyberphysical interfaces, the ROTOR unifies multi-touch and tangible interaction in a single application. Users can use the application just with multi-touch interaction. However, users can purchase optional ROTOR controllers, to unlock the ReacTable ROTOR's full potential, bringing the ReacTable tangible music experience to tablets. My notion of CPI extends the capabilities of the ReacTable ROTOR by including the notion of soft tangibles, which is not considered in the ROTOR's interface.

Figure 4.11: **ReacTable variations.** *a) The ReacTable Mobile is a purely multi-touch interface. b) In line with the my work and the notion of CPI systems, the ReacTable ROTOR combines multi-touch and tangible interaction for commercially available commodity tablet devices.*

4.11.2 LAVA mediation engagements

One objective of the platforms presented is to explore hybrid interaction approaches to extend the capabilities of multi-touch and tangible interaction into composites that exceed the capacities of any approximation taken individually. This goal was more closely realized with the Entrada Platform, in particular with its tablet interface (Fig. 4.6b). Combining tangible and multi-touch interaction into a single experience provided opportunities to explore a number of facets of the LAVA heuristics. Figure 4.12 explores these perspectives. The rows compare tangible interaction, multi-touch interaction, and their hybrids or composites. The columns depict the facets of LAVA. In particular, "Actionability" is contemplated from two perspectives: discrete actions, and continuous actions.

I will consider legibility in terms of the 2D interfaces (since this is usually associated with multi-touch platforms) in comparison to tangible interaction. 2D interfaces offer high capacity for customization of shape, color, and even the ability to weave animations into on-screen elements, allowing for great freedom and control of what each element represents. One arguable limitation is that elements in 2D interfaces are limited to producing visual stimuli. Tangibles, on the other hand, can produce multi-sensory stimuli, including, but not necessarily, the use of vision. In particular, the ability of tangibles to be held by users, letting them perceive materials, textures, weight, temperature, among others, can give developers a larger sensory bandwidth to work with, albeit exploring some of these possibilities (e.g. the equivalent to 2D animation is shape-shifting, actuated elements) can greatly increase complexity and cost. Hybrid, or composite approaches have the potential to complement 2D interfaces and tangibles (e.g.) by associating physical objects with meaningful (animated) 2D representations.

A similar argument can be made in relation to the "actionability" of tangible and multi-touch interfaces. Shape, texture, materials, etc. can hint which actions can be performed with a physical control with a larger sensory bandwidth than 2D interfaces, while these can implement movements and animations more easily than with physical objects. To avoid this repetition, I chose to analyze actionability in the context of the Entrada platform as it relates to the types of actions performed. Two types of actions were provided by the tablet interfaces. *Discrete actions*, such as the selection of a slide, or a function, and *continuous actions*, such as zooming in or out an image, or rotating an object. As mentioned earlier, users tended to prefer the use of tangibles for continuous actions, and the use of multi-touch buttons for selecting functions or slides. One possible explanation is that users (consciously or unconsciously) preferred interaction modalities that matched "natural" affordances. The continuous rotation of a knob was preferred when continuously zooming an image. The discrete action of selecting a single slide from a set was more commonly done by discretely clicking a button. Here, hybrids or composites also seem to present an optimal option. In terms of "veritability", I classify tangibles as less veritable than multi-touch interfaces. This is mostly due to the popularity (and currently even expectation) for multi-touch interaction. I ranked tangible interaction as more aspirational, given the perceived enhanced interest of users for this mode of interaction. Important to note that this maybe a response to the "novelty" factor, and not an intrinsic property associated with tangibles.

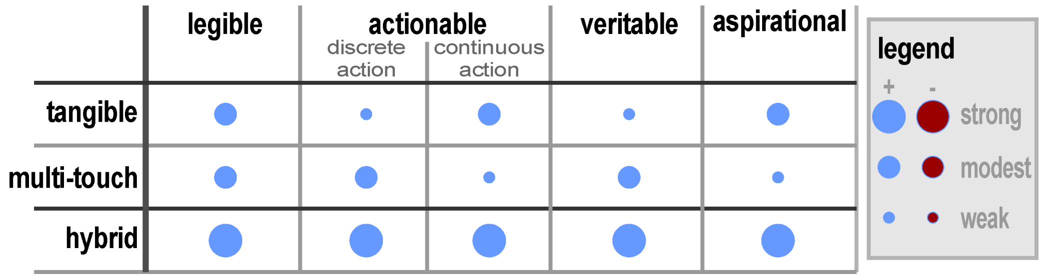


Figure 4.12: **LAVA engagements by combining tangible and multi-touch mediations.**

4.11.3 Final Remarks

In this chapter, I have introduced the approach mixing multi-touch with "hard" and "soft" tangible interactors. I illustrated this with two groups of prototypes that support the creation, presentation, and engagement with computationally-mediated scientific posters, as created by undergraduate students. Within these systems, we and our content creator collaborations have begun to explore combinations of multi-touch and tangible interactions with dial-like (hard and soft) tangibles.

Neither the templated nor freeform approaches were inherently "better" than the other. The templated approach facilitated greater focus on content development, increased consistency, and altogether raised the lower-bound bar on interaction quality and consistency. The second, more freeform approach allowed greater creativity and flexibility, sometimes facilitating standout results, while also allowing more marginal variations and sometimes distracting from content creation.

As with other multi-device digital poster systems such as [7], the addition of horizontal interactive surfaces extends the per-"station" footprint of ours versus traditional paper posters. Cost, weight, and logistics considerations are also present. With these trade-offs comes the potential for greater interactivity, and (again as per [7]) the prospect for interacting with many different posters at a given station. By analogy, web page interactions also have different physical "space requirements" and functional potentials than do paper pages. Similarly, we see CPIs and paper posters as holding both similarities and differences, with neither being a direct replacement for the other.

While my work focused on scientific posters, hopefully the analysis of the ReacTable line of products has begun to show that it is possible to generalize the concept of CPIs beyond that context. Looking at the bigger picture, I hope this work helps point to a future where tangible interfaces are not intrinsically segregated, but intimately integrated in hybrid ecologies of systems that combine a number of representational forms, scales, and interaction paradigms.

Chapter 5

Combining Interaction Modalities: Tangibles and Virtual Reality

"Was it Laurie Anderson who said that VR would never look real until they learned how to put some dirt in it?" William Gibson, author of Neuromancer

Following my work combining tangible and multi-touch interaction, this chapter explores an ecology of cyberphysical devices that implement combinations of tangible and virtual reality interaction with special focus on the design and fabrication aspects. The VR systems and environments created are sometimes immersive and sometimes non-immersive. Interaction often has a rotation-based component, however, diverse representational forms are also explored.

Presence and *immersion* are two key properties of engaging immersive virtual reality experiences. Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another. Immersion is a psychological state, characterized by perceiving oneself to be interacting with an environment that provides a continuous stream of stimuli, and experiences [289]. Immersion is related to technical aspects that can help replacing real-life for synthetic stimuli, and promote isolation from the real world. Arguably, providing VR users with synthetic visual, auditory, and haptic stimuli makes it possible to accurately generate almost any virtual environment, in a believable and immersive manner [89].

Current consumer virtual reality devices typically combine headsets, controllers, and other

Figure 5.1: **Combining tangibles and virtual reality.** *A number of efforts combining tangibles and virtual reality, with co-located and tracked; immersive and non-immersive strategies.*

peripheral sensors for tracking users and artifacts in the virtual environment. While headsets may provide rich visual and auditory information, tangible interaction within VR is mostly limited to haptic feedback from generic-purpose controllers as (e.g.) Oculus Touch [30], and HTC Vive controllers [64]. Higher fidelity haptic feedback can be achieved with devices like CyberGlove III [34], Manus VR [43], among others, but they can ramp-up production costs very quickly, and still lack accurate vibrotactile feedback for complex objects. The lack of high fidelity interactions and engagement with tangibles within VR can also be attributed to the complexities of incorporating custom-built tangibles to VR systems, as solutions may involve building custom hardware and integrating additional layers of software (e.g. for network communication, and tracking).

Lessons learned in research that explore digital fabrication approaches for the augmentation of commercially available commodity devices (complementary to custom-built solutions) may contribute to evolve the current state of tangible interaction within VR. The combination of Microsoft Surface Dials [45], 3D printing, spatial tracking (e.g.) with the HTC Vive trackers [65], and software development environments, such as Unity 3D [21] - both as particular products, and as representatives of broader classes of technology – can be applied to overcome the existing challenges.

Dials can be tracked in the virtual environment, and facilitate constrained parametric interaction, providing active and passive haptic feedback. 3D printed (sometimes capacitive) elements can add physically-representational forms to general-purpose devices for evocative haptic feedback in VR immersive environments.

I start this chapter by describing the design and fabrication aspects of two preliminary projects, which combine tangibles and VR. The first employs co-located digital representations and physical Microsoft Dials. Then, I describe a system which augments a coffee mug with a Microsoft Dial in an envisioned interface that combines immersive and non-immersive interaction with the mug controller being used in both interaction modalities. Following the preliminary projects, I describe several artifacts created for a half-day tutorial session presented in March 2018 at the IEEE-VR conference, and discuss strategies to effectively combine tangibles and virtual reality.

Beyond the specific functionality of each system, all projects employ approaches to allow the objects created to be reproducible (via 3D printing or laser cutting), employ commodity devices such as tablets, and regular consumer-grade multitouch screens, and utilize vintage or niche devices, such as 5-year-old smartphones, and the Microsoft Surface Dials. This is aligned with the goal of creating systems and tangible devices which are accessible to the broadest number of people possible. Fig. 5.2 shows several of the systems developed.

5.1 Co-located Digital and Physical Tangibles

As my initial exploration of systems that combine tangibles and VR, I co-created, with three other colleagues, an immersive VR simulation in which an active physical knob (a Microsoft Surface Dial) was co-located with its digital representation. By precisely matching the digital representation with the physical one, users were able to obtain a believable haptic feedback, which when combined with the auditory, and visual stimuli generated by the VR system, contributed to an enhanced perceived immersion, and sense of presence.

5.1.1 A Moral Dilemma Virtual Reality Simulation

What people say they would do may not necessarily be the actions they actually follow through with, given a particular situation. This concept has been analyzed through psychological research concerning decisions in moral and ethical dilemmas, such as the Trolley Problem [248],

Figure 5.2: **Designing and fabricating tangibles for VR:** *Several systems developed combining tangibles and VR. All systems were part of a half-day tutorial session presented in March 2018 at the IEEE-VR conference.*

where a person must decide to allow a trolley continue on its path and kill five people, or purposely alter the path of a trolley and kill one person, but save the five others. Several previous studies have exercised the same task of posing a moral dilemma [254]. In a VR-related study, an adaptation of the Trolley Problem was created, in which the users have to choose which victims to save from a shooter [202]. In another instance, the dilemma entails witnessing racial discrimination [100].

This project also implemented a VR simulation for a variation of the Trolley Problem. Inside a fictitious power plant about to explode, users may open and close two doors remotely, by using a dial on a control panel to choose which workers to save. By not actively selecting a second door with the dial, one worker is saved, and five die in the impending explosion. By actively turning, and clicking the dial to select the second door, five workers are saved, but the user has to accept that his actions caused one of the virtual workers to die. Figure 5.3a shows a user interacting with the system during a presentation session.

While a full description of the simulation would contain information about the steps taken toward (e.g.) creating a sense of urgency in the users, this short description focuses on the tangible interaction facet of the project. A more detailed description of the project, including development

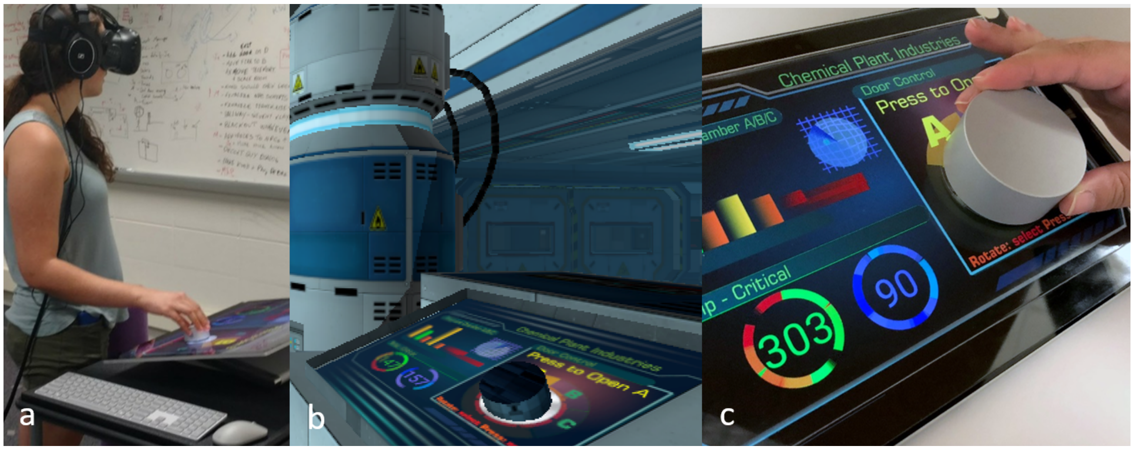


Figure 5.3: **Virtual reality simulation with co-located virtual and physical dials** *a) User interacting with a Microsoft Surface Dial. b) Virtual dial, and control panel, as seen by the user when wearing the HMD. c) Physical control panel on a tablet. An animated simulation of the control panel is displayed in the physical control panel.*

milestones can be found in Appendix D.

5.2 Implementation Strategies and Tools

5.2.1 VR Room Arrangement

To effectively bring co-located tangibles into VR environments, I had to observe a number of constraints and carefully plan the space we occupied. I developed the VR simulation in real-life scale, and accounted for the the shape and size of the room in which the simulation was going to be presented. Also, the shape and size of the physical control panel (in reality a four-wheel cart) was also taken into consideration when designing the virtual control panel.

Because users were allowed to walk multiple virtual rooms, each room was carefully designed to have the space occupied by the physical control panel as a *non-walkable* area, otherwise users could inadvertently bump into the physical cart representing the control panel. Three strategies were employed: a virtual control panel was co-located with the real one (cart), another (virtual) object with similar size was co-located with the cart, or the area occupied by the control panel was replaced by a virtual wall.

To promote immersion in users about to experience our VR simulation, and "entertain" people waiting for their turn, we added two screens to our room. One of them, in vertical position, showed the title of our simulation, and displayed images from the HMD's point of view. The other display was positioned horizontally, with the Microsoft Surface Dial on top, representing the control panel. Instead of a "dead" black display, I chose to develop a partially functional Python-Kivy interface. The interface (Fig. 5.3c) had a spot for the Dial, and displayed in real-time which doors were opened, and closed as the user turned the physical dial. The addition of the the interface, contributed positively to the overall immersion of the experience.

5.2.2 Connecting the Microsoft Dial to Unity 3D

I used a Microsoft Surface Dial without any augmentations to control the doors in the moral dilemma simulation. The first challenge faced was the lack of native support in Unity 3D for the Microsoft Surface Dials. While developing code to tightly couple the Dial to the Unity 3D platform was technically possible, arguably with its advantages (e.g. reduced overall system's complexity), I chose to loosely couple the Microsoft Dial to Unity 3D, hoping that this strategy could generalize toward coupling the Dial to a number of other systems, with possibly little to no additional coding necessary.

Toward that goal, I implemented an architecture as shown in figure 5.4. The Microsoft Surface Dial is paired via Bluetooth to a Windows-based system. Sometimes a tablet, sometimes a desktop machine (e.g. the Microsoft Surface Studio desktop machine). A Python-Kivy application [40] receives callbacks from the Microsoft Surface Dial, and sends specific OSC [293] messages to the host system running the VR application. Note that Kivy itself was not compatible to the Dial, so internal Kivy libraries, related to input devices, had to be adapted. Appendix **??** shows an extract

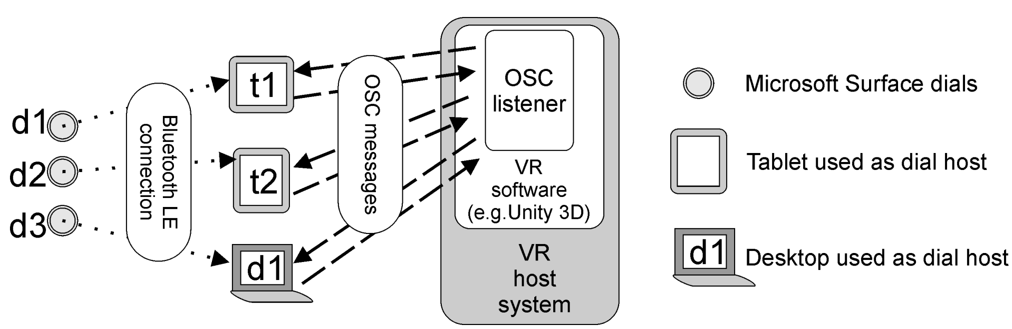


Figure 5.4: **Architecture to loosely connect surface dials to VR systems.** Each Microsoft Surface dial is paired to a dial host via Bluetooth LE. Tablets or desktop machines may be used as dial hosts. Rotation, button clicks, and IDs are sent by the dial hosts to the VR system via OSC messages.

of the Kivy-library adapted to receive Dial input.

While I could have chosen several other languages to build an application to "convert and relay" Dial input into OSC messages (in other opportunities, versions in C-sharp were created), I chose to implement it in Python-Kivy since it gave me the opportunity to develop multi-touch interfaces for the machine the Dial is connected to.

On the host machine running Unity 3D, I employed UniOSC [61]. This third-party package provides easy configuration for sending, and receiving OSC [293] messages generated from Microsoft Dial inputs, allowing me to map the actions of rotating, and clicking the physical Dial to the virtual environment.

5.3 Challenges with Co-located Artifacts

Besides the initial setup efforts to precisely co-locate physical, and virtual artifacts, I faced the challenge of maintaining the objects in their positions as users walked around the room, and manipulated them. Keeping real-world objects' positions constantly matching their virtual counterparts was important to maintain usability of the simulation, and to avoid breaks-in-presence [249]. While the task of keeping the cart with the control panel from moving was as simple as locking its wheels, users would constantly move the Microsoft Dial around, creating a miss-match between the virtual and digital entities (Fig. 5.5).

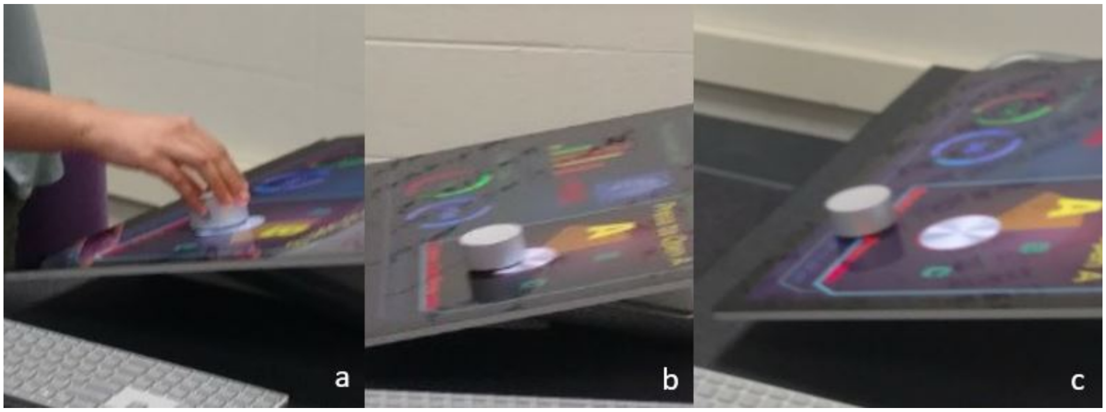


Figure 5.5: **Without constraints, users would move the Microsoft Dial from its co-located position, possibly creating breaks in presence.** *a) User manipulating dial for the first time, position of the physical dial nearly matches the virtual one. b) After the first interaction with the dial, half of the dial is out of the co-located position. c) A couple interactions later, usability is compromised. Sometimes users would not be able to find the dial without external help, or removal of the HMD, generating breaks in presence.*

Drawing lessons from (e.g.) [259] and [246], I fabricated an adaptable physical constraint system, based on two acrylic elements. The external element, functions as a frame. Inspired by [151], it can be firmly attached to the tablet screen with a number of micro-suction tapes [18]. The second element is held in place by the frame (external element), and has a slot for the Microsoft Dial. The slot serves as a physical constraint, and keeps the Dial from moving in relation to the display underneath. This two-piece arrangement allows this physical constraint system to be adapted to multiple interfaces, without the need to replicate the frame. Figure 5.6 details the elements of the acrylic constraint, including the micro-suction tape elements employed.

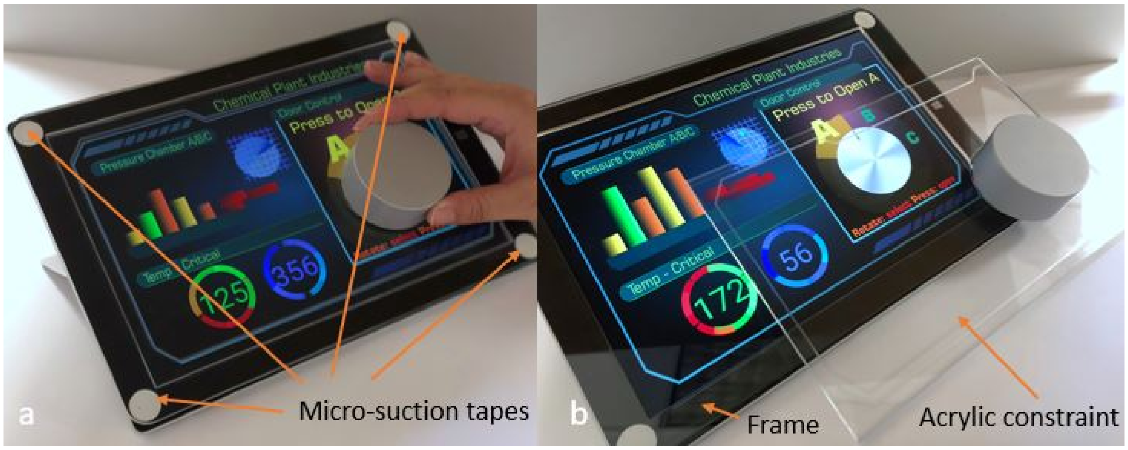


Figure 5.6: **Physical constraint for dials.** *a) Four micro-suction tapes [18] attaches the frame to the tablet. b) A slot in the acrylic constraint keeps the Dial from moving.*

5.4 User's Observed Reactions and Comments

Besides the technical knowledge gained with this project, I observed several encouraging reactions from users related to the use of tangibles in combination with the virtual reality simulation. Besides my own observations, eight students, from those who experienced the Moral Dilemma simulation during presentation day made informal comments about the experience shortly after experiencing it.

One repeated reaction I observed was that users pressed hard on the Dial, and sometimes violently turned it, when they were experiencing the most stressful moments of the simulation (e.g. when the building was about to explode, and they had to choose one of the doors.) This indicated to us that the simulation was achieving a considerable level of immersion.

Another fact that indicated high levels of immersion was that when a door, which was expected to open or close, did not react at the speed imagined by the user, the user would press the Dial harder, and repeatedly. Some users even commented that they were afraid to have broken the device, and apologized after the simulation. We had to explain that our team was happy to see that kind of reaction, and there was no need for apologies.

Users also commented that the combination of visual, audio, and tactile stimuli made the experience more engaging. Since the simulation involved a stressful situation, users felt that being able' to press and hold *something* made the experience more real, which would have not been possible if the physical dial was not present. Figure 5.7 shows the reactions of one of the users.

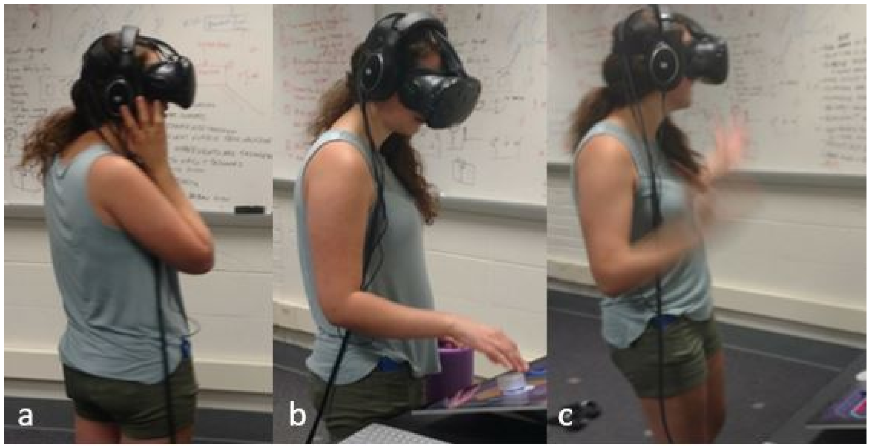


Figure 5.7: **Reactions from user while experiencing the VR simulation.** *a) User is trying to concentrate and listen to the instructions at the beginning of the simulation. b) User interacts with the Dial. b) User has a strong reaction as the virtual building collapses.*

Following the Moral Dilemma project, I implemented another system which combines tangibles and Virtual Reality. This time, I sought to combine immersive and non-immersive VR experiences, with a mug-controller as the unifying element between the two modalities. In addition, the mug-controller gave me the opportunity to begin exploring artifacts with forms beyond the cylindrical dials.

5.5 Combining Immersive and Non-Immersive Tangible Interaction

We consume information displayed on screens of many scales, shapes, and arrangements. We are surrounded by the screens of our smart-watches, smart-phones, computers, TVs, digital outdoor signs, and beyond. Recently, a new set of screens have been made available to the mass-consumer market: head-mounted displays, in the context of virtual reality systems.

More often than not, content that may have been created for the scale, and capabilities of a particular screen may be viewed in several others. Invoking Mark Weiser's vision of artifacts in the scale of tabs, pads, and boards [277], a movie made for the large screens of movie theaters may be watched on the inch-scale display of a smart-phone, a foot-scale tablet, or with the yard-scale display of a TV. The type of content, the context, and even personal preference may influence form-scale-content choice. Content creators, and consumers may consider the strengths, and limitations of each format, and choose accordingly.

VR may also serve as a medium for watching movies [28], replicating the desktop environment of a computer [253], or used for social networking [25]. However, considering current HMD technology, while it enables users to tap into their natural ability to process spatial information (e.g., by immersing them in virtual environments) [219], watching movies, reading long texts, and browsing web-sites are still tasks usually associated with 2D screens [85].

When considering (e.g.) scenarios involving scientific content, with prospectively equal opportunities for creating 3D (e.g., 3D models, data clouds, etc.) and 2D (e.g., text, images, videos) content, how should one choose the optimal combination of interaction modality, form, and scale for the content? A 2D interface would fail to optimally communicate 3D content, while a VR environment would fail to optimally communicate long texts.

Instead of choosing between those two options, I began to explore a platform that enables the creation of interfaces that combine non-immersive (2D), immersive VR content, and interaction. Content creators can choose which content to display in the 2D interfaces, and which to display inside VR environments. A key aspect is that for the most part, content creators, and users can choose which format best suits them at any given moment. In this context, I do not consider neither medium as inherently "better" than the other. My aim is to enable the development of interfaces that work optimally in the spectrum of purely 2D, to purely 3D content, with my greatest interest on systems that combine both.

In this section I describe the process of developing a prototype created during a semester-long class project. The prototype has 2D, and VR content that can be engaged by users. It implements a system developed for a fictitious coffee shop, in which the tables are multi-touch screens, and users can engage 2D, and VR content while drinking their choice of freshly brewed coffee.

5.5.1 The Kubistor VR Coffee Shop

The word Kubistor is a composition of two German words. kubism [286] was one of the dominant visual art styles of early 20th century. Cubist paintings show multiple views of a subject concurrently. Tor, is the German word for gate. The Kusbitor Coffee Shop provides the user with

Figure 5.8: **Kubistor Coffee Shop interface.** *a) 2D inteface. The mug controller controls the on-screen dial. b) Detail of the VR dial, as seen by the user wearing the HMD. c) User with the HMD using the mug to navigate the VR environment.*

an experience that combines 2D, and VR interaction modalities in a single system (Fig. 5.8).

The Kubistor coffee shop, uses multi-touch displays as tables. Multi-touch, and the mug-controller may be used to navigate, and interact with the content in the physical horizontal display. Users can sip coffee, browse the Internet, read, and watch videos.

Users can also choose to immerse themselves in VR. When they do, they are prompted to wear an HMD. Users can walk around the physical tables, inside the tracked space of HTC Vive devices, and explore several virtual spaces. In this mode, the mug controller is used to navigate the VR world.

Users can experience most of the content in 2D, and in VR, depending on their personal preference. However, some content is exclusive to one modality, or the other. Users can visit galleries of images from Brazil, India, and China both in VR, or in 2D. However, they can only navigate VR simulations of coffee shops from each country when in VR mode.

5.6 Design, Implementation, and Challenges

The physical environment of the prototype for the Kubistor Coffee Shop was built in a squared space, tracked by an HTC Vive VR system. A horizontal 55-inch multi-touch display was connected to a machine running a 2D interface, developed with the Unity 3D platform [21].

A second machine was responsible for the virtual reality simulation. In the virtual reality environment, I employed similar techniques from the previous project to co-locate the physical, and virtual table-displays.

One challenge during design was to define an interaction paradigm that could function for

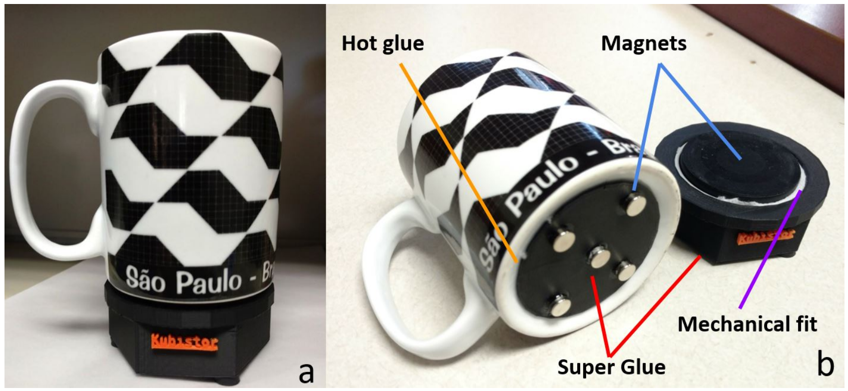


Figure 5.9: **Mug Controller.** *a) Detail of the mug controller. b) Several strategies were employed to assemble the mug controller. Hot glue attaches a 3d printed disc to the mug. Magnets connect the mug to the dial. The Microsoft Dial is tightly fit to the 3d printed base. Super glue is used to attach the magnets, and conductive rubber pads to the base of the mug.*

users with, and without the HMDs. Since the chosen scenario was a coffee shop, I sought to find a way to allow users to continue to drink coffee when migrating from 2D to VR interaction. In this context, the mug controller was conceptualized. The mug controller can be held by one hand, while the other hand can rotate, and click the knob at the bottom of the mug. This way, users can prospectively drink coffee, while interacting with the VR environment. Connection of the Microsoft Surface Dial in the mug, with the host system employs the same approach as previously described. Contrary to the previous system, this time the Microsoft Dial is tracked when in contact with the 2D display.

In 2D, when the mug is pressed, a small radial menu appears around its the base. Rotating the mug allows the selection of multiple options. In VR, by clicking the mug, a large radial menu appears in front of the user, and rotating the mug allows selection of options.

5.6.1 Fabricating the mug controller

To create the mug controller, several materials and strategies were employed (Fig. 5.9). One of the objectives what to couple the Microsoft Surface Dial to the base of the mug in such a way that it could be removed (e.g.) for washing it. To that end, a thin (approx. 2 mm) flat round piece of 3D printed thermoplastic containing four magnets was permanently attached to the bottom of the mug with hot glue. Since the bottom of Microsoft Surface Dials also contains magnets, I was able to connect each piece with enough strength to allow users to safely manipulate the mug and the Dial.

To account for aesthetics, black PLA thermoplastic was used to 3D print a housing for the Microsoft Surface Dial. The Microsoft Surface Dial was fit to this piece tightly, without the need for any additional adhesives.

These three strategies of using adhesives (e.g. hot glue), magnets, and mechanical fit employed in this project were later extended, and used in a number of different projects combining tangibles and virtual reality.

5.7 Exploring Fully Tracked Devices

Having explored scenarios with co-located dials, and scenarios combining immersive, and non-immersive VR simulations, I next describe one instance involving a tangible fully tracked in the 3D space.

While it is possible to custom build trackers, with prospectively several advantages over purchasing them (e.g. having freedom to customize its size and shape), I decided to work with a commercially available variant, the HTC Vive tracker [65], due to its wide availability, and popularity.

To this end, I designed and developed, with Ayush Bhargava, a fellow Ph.D. student at Clemson University, the VRFishing Rod simulation, which was part of a tutorial session at the 2018 IEEE VR conference.

Building upon the experiences described previously in this chapter, the tutorial explored the topics of tracking, augmenting, and combining fabricated, and commercially available commodity devices within virtual reality environments. In this context, I designed and built the *VRFishing Rod*, the *VintagePong Controller*, among others (appendix F – Fig. 12, 14). The 3-hour workshop was attended by aprox. 50 participants. They were presented with theory, hands-on activities and demos, giving them a chance to try out several devices.

In appendix F, I describe the design, build, and deployment of the VRFishing Rod simulation through the lenses of the *fullborn framework* discussed there. In this chapter, I'll focus on the structure of the object, and its connection architecture.

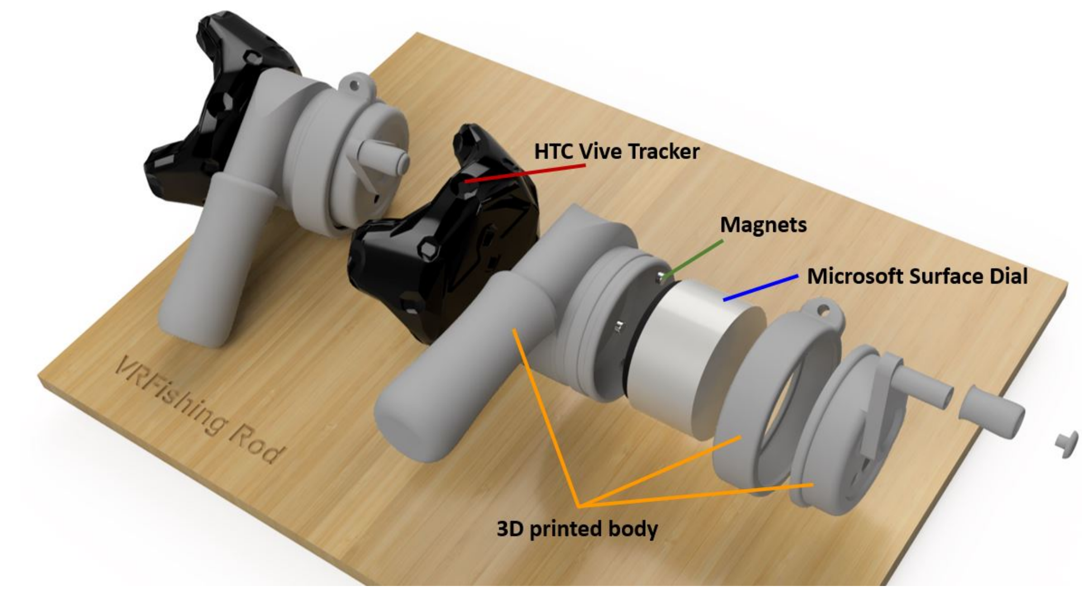


Figure 5.10: **Components of the VRFishing Rod.** *The Microsoft Surface Dial inside the fishing rod allows sensing rotational movements, and dial presses. The HTC vive Tracker allows tracking in 3D space.*

5.7.1 VRFishing Rod Overview and Connection

The VRFishing Rod is composed of three main components: a 3D printed body, a Microsoft Surface Dial, and a HTC Vive tracker. Fig. 5.10 detail those components.

Similarly to previous approaches, the Microsoft Surface Dial is loosely connected to the VR host system, while the HTC Vive Tracker connects natively to Unity. The complexity is, therefore, not greatly increased by the addition of the HTC Vive tracker (Fig. 5.11).

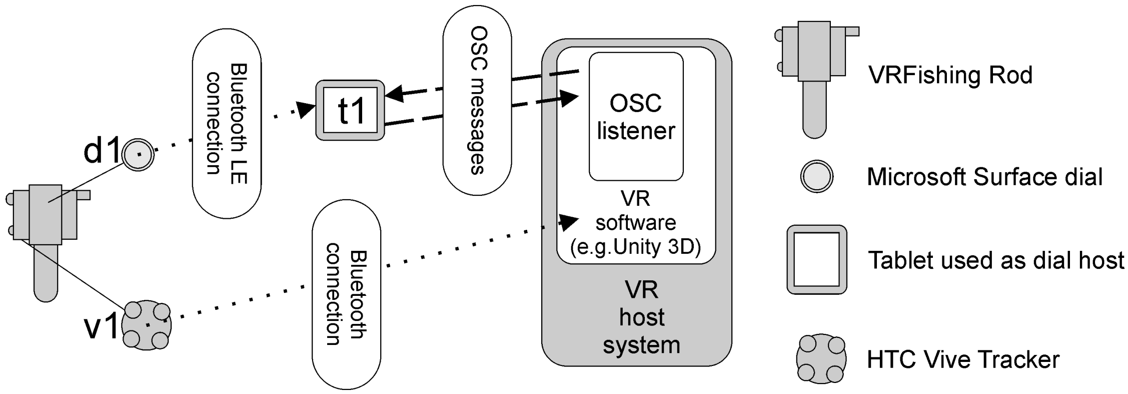


Figure 5.11: **Connection Schema for the VRFishing Rod.**

5.8 Discussion

5.8.1 Microsoft Dial based systems

The efforts described in this chapter, toward combining tangibles and VR, demonstrate a number of recurring themes of my work: proposing, and implementing software strategies to connect physical objects to computational systems, fabricating new artifacts, and augmenting existing commercially-available ones, often re-purposing them toward new applications, exploring combinations of interaction modalities, and exposing the systems developed to a number of people, often out of the lab environment.

Most of my work evolved around utilizing Microsoft Surface Dials in a number of forms. Sometimes naked Dials were used, sometimes the Dials were augmented with 3D printed parts, or attached to other artifacts. While I find the cylindrical form-factor of the Dials immensely attractive to the type of adaptations, and augmentations my work invites, the same cannot be said when it comes to Microsoft Dial's software interface (API).

The Microsoft Surface Dial is viewed by Microsoft as a peripheral such as a keyboard, or a mouse. These devices are based on the Human Interface Devices (sometimes called the Human Input Devices) or HID specification [60]. A limitation of this approach is that input from multiple devices of the same kind are not recognized individually. For example, connecting two keyboards does not cause programs to have two cursors on screen. Connecting two mice will not cause the system to display two pointers.)

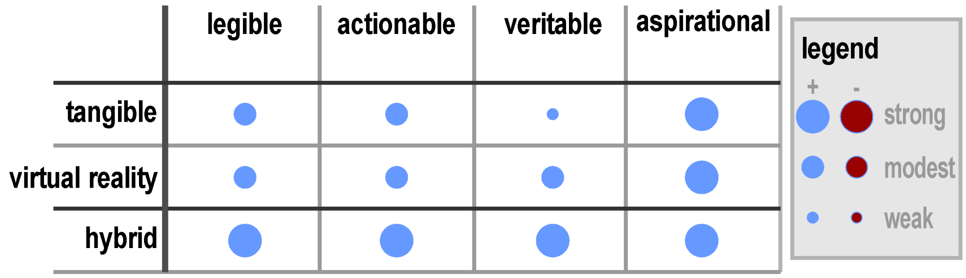


Figure 5.12: **LAVA engagements by combining tangible and virtual reality mediations.**

In most systems involving tangibles, being able to identify individual input from multiple artifacts is a necessary feature. While it is possible to implement extensions to the HID protocol for the Dials (also called wheels withing Windows operating system), this solution requires each new system interfacing with the Dial-as-a-tangible to also be adapted to work with a new HID-extended Dial driver.

I chose to loosely connect the Microsoft Dial with other systems, instead of adapting the HID API of the Dials. On the down side, with this approach (as shown in Fig. 5.4, and Fig. 5.11), each Dial must be connected to an individual machine running a Windows operating system. I chose to use tablets. This was not the least expensive, but was the least cumbersome solution. Dial inputs are converted to Open Sound Control ([293]) messages within the tablets, and relayed to host systems. The OSC protocol is readily available as libraries, or add-ons in a number of systems, which are able to listen and interpret to such messages.

More important than the loose coupling strategy I propose, is the recognition that operating systems still have long ways to go to help realize the vision of wide spread tangible interfaces. While this work celebrates a dial-like tangible, which is mass produced, and natively compatible with one of the most popular operating systems in history, basic capabilities relevant to the development of tangible user interfaces were still left unsupported. In October 2017, I inquired Raymond Chen, a senior developer at Microsoft, in a Microsoft maintained git-hub forum about the possibility of having Microsoft support distinction of multiple input from Dials. His answer was negative [51].

5.8.2 LAVA mediation engagements

One objective of this chapter is to explore hybrid interaction approaches to extend the capabilities of tangibles and VR interaction into composites or hybrids that exceed the capacities of any approximation taken individually. Combining tangible and VR interaction into a single experience provided opportunities to explore a number of facets of the LAVA heuristics. Figure 5.12 explores these perspectives. The rows compare tangible interaction, VR interaction, and their hybrids. The columns depict the facets of LAVA.

Legibility in VR can be explored, in many ways, similarly to legibility in tangibles. Shape, volumes, colors, and materials can be (re)created to give an artifact or control a meaningful representational form. However, considering current VR technology (in particular consumer grade), VR is limited to providing visual, auditory, and (limited) tactile feedback – mainly provided by generic-purpose controls with some form of vibro-tactile capability. Texture, weight, temperature, are not usually present in VR simulations. This is something that tangible interfaces can contribute to the legibility of systems within VR environments. A similar argument can be made in relation to actionability. Substituting general-purpose controls for special-purpose ones, effectively matching visual appearance with form, leads to an enhanced perceived affordance (Rotating a virtual dial on screen while holding a physical dial is more intuitive than rotating it while holding a generic-purpose controller). This may also have impacts in other factors associated with actionability, such as learnability and memorability. The "explicit" affordance of tangibles may render them easier to learn and remember, when compared to (e.g.) an HTC Vive controller, which has at least a half-dozen triggers and controls.

In terms of veritability, both systems share a sense of novelty. However, given VR's current mass-market adoption, I consider it more veritable than tangible systems. I consider both to be aspirational, capturing the minds of users in what such systems may promote, and become as they mature.

Chapter 6

Evaluating the Effects of Calibration on the Near-field Size Perception of Tangibles in VR

"Reality is merely an illusion, albeit a very persistent one." Albert Einstein

"We can only see a short distance ahead, but we can see plenty there that needs to be done." Alan Turing

While the previous chapter explores combining tangibles and VR from a design and fabrication perspective, this chapter analyses such systems from a perception-action point of view, with potential implications on how we design and fabricate tangibles for interfaces combining tangible and VR interaction.

It is often important to create immersive virtual environments (IVEs) and user interaction metaphors that closely replicate real world situations, specially for simulations involving training [239], education [217], rehabilitation [117], and therapy [137]. However, distortions in human perception are known to potentially degrade training outcomes, experience, and performance in VR [121]. For example, users find it difficult to provide accurate distance estimates while wearing HMDs, consistently underestimating distances between themselves and other objects in IVEs [288, 166].

We perceive the environment, at a low-level, based on the sensory information provided by our basic senses (e.g. of vision, smell, touch, taste, etc...). However, we continuously act based on judgements that rely on higher levels of perception, such as perceived affordances [191]. For example, when we reach for a cup resting on top of a table, we don't attempt to consciously estimate the distance we must move our hands from its current position until reaching the cup, and we don't actively estimate the size of the cup in comparison to the size or our hands to judge if we can hold it. The low-level senses of proprioception, vision, and touch that support our judgement of distances and sizes, are combined into the higher-level perception of affordances, such as graspability [135]. Similar arguments can be made for our judgements of passability (our ability to walk through a door gap) [273], among others. However, since higher levels of perception are based on low-level sensory input, we need to understand basic low-level perception such as size, temperature, color, and distance to fully comprehend higher level perceptual constructs such as affordances.

Our senses, however, are not static. They are constantly being calibrated to accommodate for changes in the body and in the environment that may occur both in the long and short terms. As we grow older, throughout our childhood development, bones grow and muscle mass increases, gradually changing the relationship between motor commands and motion of the limbs [241], and we must constantly adapt to these changes. Disease and age can also gradually affect the strength of muscles. Such changes, however, can also occur quite fast.

At airports, it is common to encounter moving walkways that are designed to transport people across short to medium distances. Moving walkways can be used by standing or walking on them. While entering or exiting, and when walking, users experience a short term calibration. When walking in the walkway, users are able to quickly calibrate to the fact that with each step they take their vision perceive their bodies as moving longer distances. Upon leaving the walkway, users are again able to quickly calibrate back. It follows that to maintain performance, our brain needs to be "robust" to these short and long term changes through calibration [241].

A number of researchers have explored calibration in the real world [270, 94, 225], and in virtual environments [120, 170, 196]. Perhaps the oldest record of a visuo-motor adaptation is an 1867 report by Hermann von Helmholtz [270]. He asked subjects to point with their finger at targets while wearing prism lenses. The lenses displaced the visual field laterally. When the displacement was to the left, participants initially had errors (overshoot) in that direction, but with some practice, they learned to compensate for the visual displacement. Helmholtz observed that as soon as the prisms were removed, subjects made erroneous movements to the right of the target. This became known as an aftereffect of calibration. Rock and Harris [227] also carried out a series of experiments related to visuo-motor calibration. They used a glass surface that was just below the eye level of a seated subject and had a row of labeled rods standing upright on the glass as targets. The experiments had three parts: pretest, calibration and post-test. In the pretest they covered the glass surface with a black cloth so that the subject could see the targets but not his hands. He was asked to point at various rods from below the glass. The pretest determined the subject's responses to the tests that would be compared to the responses he would be giving after calibration. During calibration, the subject wore prism goggles for three minutes and the prisms shifted his visual field 11 degrees to the right or the left (causing a shift of about four inches at arm's length). The subject's task was to point repeatedly with one hand at the center target. During calibration, the cloth was removed, so the subject could see his hands. Initially, he tended to miss the targets due to the prisms, but quickly became more accurate. After calibration, the subjects showed a large shift in pointing with the adapted hand during the post-test.

In VR, calibration has been suggested as a solution to the consistent underestimation of distances between users and other objects that they experience while immersed in virtual environments. By interacting with the virtual environment the user experiences a training period (with visual and/or haptic feedback) which calibrates their visuo-motor perception regarding their actions within the immersive virtual environment (IVE). This has been shown to be a simple way to improve accuracy of distance estimation, without having to resort to more expensive solutions, such as graphically scaling the virtual environment [78, 121]. However, most VR research has focused on calibration associated with mid and far field depth perception.

As we interact with people, devices, and a variety of objects in our daily activities, we constantly make judgements not just of distance, orientation, color, but also size in relation to objects that are close to us, in the near field of our perception. As VR tracking technology evolves, this also becomes true in the context of IVEs, and is a central component of several interfaces proposed by this dissertation, which combine VR and interaction with tangible knobs. Understanding the perception of size, in turn, may also allow us to gain deeper understanding of higher levels of perception, such as graspability affordance. Therefore, it is important to understand the perception of size in the near-field, and possible distortions caused by immersion in virtual environments.

Several research efforts have explored the impact size and appearance of virtual and real hands have in the perception of size of objects in IVEs[177, 157, 179, 207]. However, we find a gap in the literature with regards to the effects of calibration on the perception of size of objects in the near-field while users are immersed in VR.

It is known that users perceive a depth compression in VR. Therefore, users may also find it difficult to estimate sizes in IVEs, since size and depth perception are related to each other [194]. Based on previous results related to depth perception and calibration [78, 121], calibration may also be a simple way to improve size estimation accuracy. Also, if users' perception of size can be calibrated (to some degree) to perceive physical and virtual objects of divergent sizes as having the same sizes, the development of interfaces combining tangibles and VR can potentially be simplified and costs reduced. For example, existing tangibles of a given size could potentially be used as physical representations of tangibles of identical (but not equal) sizes. Also, tangibles created with design and fabrication approaches that may not produce objects of high dimensional accuracy, but are perhaps cheaper, or more widely available, may be indistinguishable, from a perceptual point of view, from tangibles created with more accurate (and possibly more costly) approaches once users perceptions are calibrated.

In this study, we report the results of an empirical evaluation examining the carryover effects of calibration in VR to one of two perturbations on the size of tangible dials in the near-field of perception: i) Divergent Plus condition, in which the diameter of physical knobs are 10% larger in size than their virtual representations, ii) Divergent Minus condition, in which the diameter of virtual dials are 10% larger in size than the physical ones. We also examine the accuracy of estimates of diameter in vision-only and haptics-only conditions.

6.1 Related Work

6.1.1 Perceiving Tangibles in VR

Physically touching in VR has been shown to enhance realism [138]. Moreover, affordances are learned via associative relations between object properties and our actions [145] therefore, by providing users with object properties beyond vision, they are better equipped to correctly perceive the affordances of (virtual) environments and individual objects in it, allowing for more immersive VR experiences and more effective (e.g. training) simulations. Refer to chapter 2.1.2 for further related work on combining tangibles and virtual reality.

6.1.2 Spatial and Size Perception in VR

The space around us can be categorized into three main regions: personal space (near-field), action space (medium-field), and vista space (far-field). These regions may slightly overlap but, in general, personal space is the area within a typical users arm reach, action space is beyond personal space up to roughly 30m, and vista space is considered all further distances [110]. There are several known differences between spatial perception in REs and VEs. Egocentric distance – the subjectively perceived distance from the self to an object – is known to be consistently reported shorter in VEs than in REs [147], with the mean estimation about 74% of the modeled distances [223]. This distance estimation is influenced by several factors such as measurement methods, technical, and human factors. Especially for objects at a distance (beyond an arm's length), this distortion in depth perception may also lead us to perceive an object size as smaller, since size and depth perception are related to each other [208]. Size perception depends on depth cues combined with retinal size of an object. Therefore, in controlled studies investigating size perception, the IVEs created reproduce, as much as possible, environments that are rich in depth cues. In this study, as we analyse the perception of size tangibles in IVEs, a number of elements surrounding participants in the RE, such as testing apparatus, tables, computers, floors and walls were also reproduced in the IVE to provide them with rich cues, similarly to what they would experience in the RE.

6.1.3 Body-based Scaling

Another factor that may impact the size perception of objects is body-scaling. How we perceive the size depends on how we recognize the relationship between the self and the environment [208]. Body-based scaling is the notion that apparent object sizes are perceived relative to one's body, in which our body is a "perceptual ruler" in relation to which optical information is re-scaled [216]. Thus, as we perceive our own body size as large, we perceive the size of objects as smaller than the actual size, and vice-versa [178], and in VR this is specific to a participants avatar body, and independent from other avatars or objects [177]. When studying the near-field visuo-haptic size perception of tangible objects of graspable sizes, (real or avatar) hands may constitute a confounding variable that may skew the perception positively or negatively depending on each participant's own perception of the size of their bodies. Prior studies have covered the human hand when studying size perception [227], but others have also controlled for the shape, appearance and size of hands when properties such as graspability perception were studied [157, 177, 104, 179]. In this study we follow the example set by Rock and Harris [227] when studying the size perception of objects (covering the hands of participants during trials and allowing them to see their hands during calibration), we do not track the hands of users in VR.

6.1.4 Near-field Size Perception in VR

Several efforts have explored the hand as a body-based scale for the perceived size of objects. A number of efforts explore the influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects [157, 177]. Jung et al. [157] used a personalized hand (in comparison to a generic avatar hand) in VR to improve object size estimation by participants that were asked to first look at a box, memorize its size, and than go to VR to report the perceived size in two conditions: relative and absolute size matching. In the relative size matching participants were instructed to scale a virtual box with their hands to match the size of one of the two physical boxes (sizes: 15.5 or 20 cm) that they had previously seen. In the absolute size matching participants had to scale the virtual box to match an absolute size (equal width, height, and depth) of the box. The absolute size (sizes: 5 or 38 cm) was communicated verbally to them without a physical reference that could be used as a relative cue. The impact of the presence of hands was demonstrated by the fact that better estimations were obtained with personalized hands.

In another work demonstrating the role of hands as a body scale for objects in the near-field of perception, Linkenauger et al. [177] conducted a series of four studies in which participant saw a virtual ball of several sizes and had also several hand sizes. The task involved estimating the size verbally with a scale from one (bean) to 10 (basked ball). As a result they confirmed the effect of lager hands leading to perceiving objects as smaller in VR environments in a similar way as what occurs in REs [227].

I was not able to locate studies investigating the near-field size perception of tangible objects in VR when the hands (real or avatar) are not present.

6.1.5 Perception Calibration

A large number of research efforts explore visuo-motor calibration in the real world [94, 225] as well as in IVE's [170, 196] in the action space. To overcome the problem of seeing the world as compressed in VR, some suggested that users' interactions with the IVE could improve distance estimation in a relatively short amount of time [78, 154, 162]. More recent research on the effects of visuo-motor calibration in an IVE has studied the different forms of sensory feedback. For instance, Altenhoff et al. [78] investigated whether visual and haptic feedback could improve depth judgments. In that work, participants' distance estimates were measured before and after their interaction with near field targets using both visual and haptic feedback. The result of their study showed that the users' performance significantly improved after the visuo-motor calibration interactions. Ziemer et al. [301] showed that participants calibrate to a perturbed visual information or walking speed in either real world or IVE using blindfolded walking technique. Additionally, their results indicate that with imagined walking technique, calibration has an effect only when visual information was distorted. Others have explored calibration in the near-field depth estimation [119, 120]. As an example, Ebrahimi et al. [120] investigated carryover effects of calibration to inaccurate visual feedback, with participants making reach estimates to near-field targets in the IVE. In this work, proprioceptive feedback was shown to calibrate distance judgments quickly within an IVEs.

Distortions in depth perception may also lead to distortions in the perception of size, since size and depth perception are related to each other [208]. To the extent that calibration has been shown to improve accuracy in depth perception, we intend to verify the effect of calibration in the perception of size of tangible objects of graspable sizes in the near-field of users immersed in IVEs.

6.1.6 Contributions

In this study, we investigate the carryover effects of calibration of size perception to inaccurate visuo-haptic feedback, with participants making size estimates of the diameter of tangible knobs in their near-field while in IVEs.

Similarly to [227], this hierarchical mixed design study has three phases: pretest, calibration, and post-test. Participants were randomly divided in two groups, each receiving one of two feedback treatments during the pre- and post-test phases. During pre- and post-tests, the first group reported on the estimated size of knobs after observing virtual knobs through HMDs, but not being allowed to physically touch them. The second group was asked to report on the estimated size of knobs after touching the physical knobs, but not being allowed to see them (the virtual knobs were removed from the VR scene). During the calibration phase two perturbation conditions on the size of tangible knobs were introduced: i) Divergent Plus condition, in which the diameter of physical knobs are

10% larger in size than their virtual representations, ii) Divergent Minus condition, in which physical knobs are smaller, and the diameter of virtual dials are 10% larger in size than the physical ones. During calibration participants were asked to observe and physically interact with the knobs by holding and rotating the dials a couple of times. Half of the participants from each group were calibrated in the Divergent Minus condition, and half in the Divergent Plus condition.

In each of the pretest and post-test conditions participants were exposed to 16 randomly-selected distinct sizes of knobs, and reported on their perceived diameters 3 times, totaling 48 trials for each of these phases. During the calibration phase, participants were exposed to eight pairs of (virtual x physical) knobs three times, totaling 24 pairs, totaling 120 trials.

6.2 Research Questions and Hypothesis

This study aims at answering the following research questions:

- RQ1: How does visual feedback only as compared to haptic feedback only affect the size perception of tangibles?
- RQ2: To what extent does visuo-haptic fine motor interaction calibrate near-field size perception of tangible interfaces in VR?

For RQ1, *we will compare data collected in the pretest phase of the experiment. It is hypothesized there will be a difference between haptic feedback only and visual feedback only conditions in the perceived size of tangibles in VR.*

For RQ2, *it is hypothesized that calibration will occur both in the haptic feedback only and in the vision only conditions in the near-field perception of size of tangibles in VR.*

6.3 Experiment Methodology and Procedure

6.3.1 Participants

A total of 32 participants were recruited for this study, with 16 allotted per feedback condition (haptics-only or vision-only). The average age range of participants was 24 years and 12 of the participants were females. All participants had normal or corrected-to-normal vision. They received ten-dollar Amazon gift cards as financial compensation for their participation.

6.3.2 Apparatus and Materials

6.3.2.1 General Setup

Figure 6.1 depicts the apparatus developed for the experiment. Participants were sat and positioned between the reporting screen – a vertically oriented, large (approx. 55 inches diagonal) multi-touch screen and the tracking table – a small (14" x 20"inches) rectangular surface capable of tracking the rotation of removable 3D printed dials. Participants were also equipped with a VR head-mounted display.

Figure 6.1: **General setup** *a) Participant sitting between the tracking table and reporting screen while wearing a head-mounted display. b) Detail of the participant holding one of the knobs. c) Participant reports perceived size by touch. d) Several of 3D printed the knobs.*

The tracking table was developed to track the rotation of 3D printed dials of multiple diameters. The device utilizes a Microsoft Surface Dial underneath the wooden surface to sense rotation. Sixteen dials of distinct diameters were 3D printed (eight base dials with diameters (in mm) of 40, 45, 50, 55, 60, 65, 70, 75, and eight with diameters increased by 10% in relation to the base set (in mm): 44, 49.5, 55, 60.5, 66, 71.5, 77, 82.5). Since all 3D printed dials share a similar mechanical coupling structure, dials can be easily coupled to the Microsoft Surface Dial underneath the tracking table, and can be switched in seconds. To ensure that the the tracking table remains co-located with its virtual counterpart, two clamps firmly attach the tracking table to a desk.

All 3D printed dials were designed with the same height and general appearance. The only variable design characteristic is their diameters. All dials were fabricated using 1.75 mm HatchBox gray PLA [68], and were 3D printed using the FDM 3D printer Original Prusa I3 MK3 [72] with 0.4 mm nozzle. Figure 6.2 shows details of the tracking table.

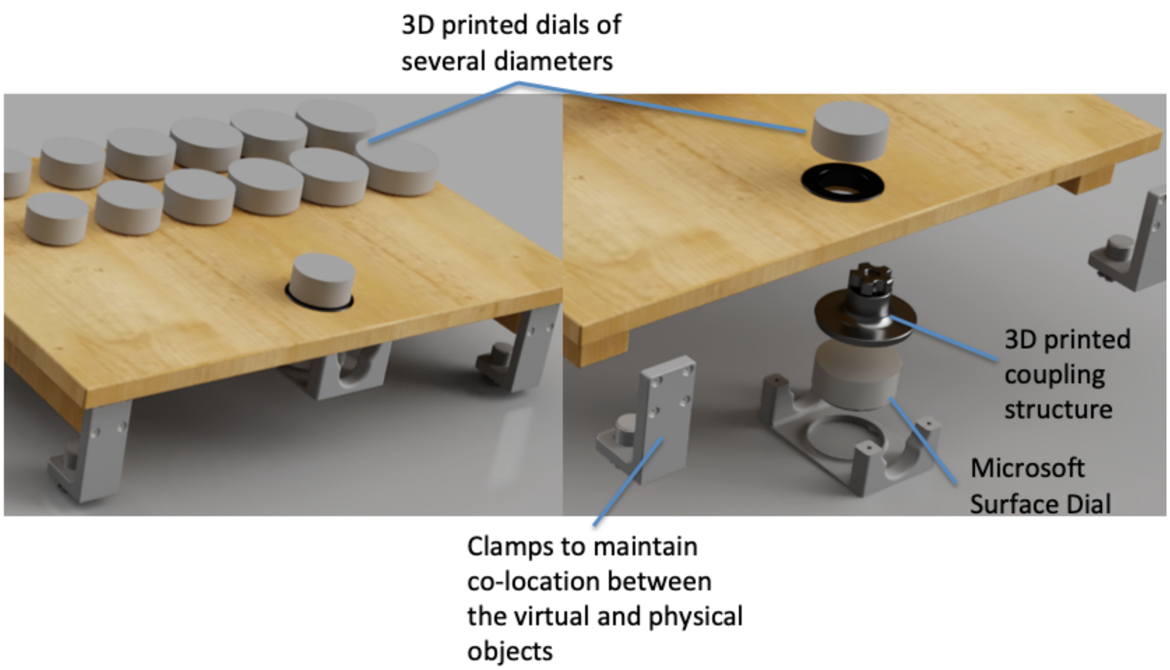


Figure 6.2: **Tracking table** *A Microsoft Surface Dial underneath the wooden table, augmented with 3D printed structures, allows multiple 3D printed dials to be coupled and manually switched in seconds.*

The reporting screen was developed so that participants can report the perceived diameter of knobs by changing the size of a circle displayed on the screen. Participants can change the size by sliding their fingers anywhere on screen to the left of the message bar, and press the message bar (when appropriate) to confirm their choice of diameter. I employed a Microsoft Surface Studio as the hardware platform, and built the reporting screen interface with Unity 3D. Figure 6.3 shows the reporting screen and details of its interface.

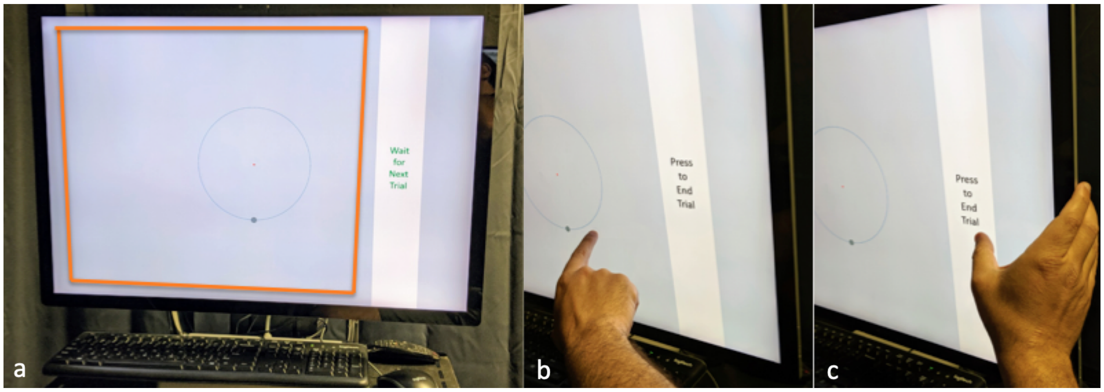


Figure 6.3: **Reporting Screen** *a) A Microsoft Surface Studio was employed as a multi-touch screen surface. The interface developed has to areas, the area highlighted in orange is the reporting area. To the right, we find a bar that serves both to give messages to the participant, and as a button that the participant presses to accept a reported diameter. b) Participant sliding his finger anywhere on screen to chose a diameter. c) Participant pressing the button/bar to report the size.*

Besides the reporting screen, and tracking table the experiment also consisted of a desktop machine running the VR simulation and exchanging messages with both the tracking table and the reporting screen. We utilized a desktop machine with the Intel Xeon W-2123 CPU, 64 GB of RAM and an NVIDIA GeForce RTX 2080 graphics card. Figure 6.4 shows details of the architecture developed to support this experiment.

6.3.3 Selecting the Reporting Strategy

A number of reporting strategies have been employed such as verbal reporting [177], physically scaling a virtual 3D object in VR [157], visually matching objects by pointing, or drawing in the RE [227], and matching a virtual on-screen image with a physical object (using the keyboard arrows to set the sizes in a non-immersive simulation) [179]. None of the previous work identified adopted our approach, in which the size of the perceived object is reported by interacting with a physical multi-touch screen, co-located with its simulated replica in the IVE.

One reason for this approach is to avoid having users verbally express the perceived sizes since that would be too imprecise. While tracking hands and fingers to use as a reporting strategy was technically a possibility, we wanted to avoid the influence of avatar's hands as a body-based scale, as discussed in section 6.1.3. Besides, participants could also possibly hold the posture of their hands after touching the dials in the haptic condition, which was not desired.

By having participants interact with the vertical multi-touch screen, participants report the perceived sizes with different channels (or body actions) from the ones they used to perceive the dials. Participants perceived the size either by looking, or by holding and rotating the dials horizontally, and reported by sliding (usually a single finger) on a vertical screen. This kept users from just transposing the perceived haptic size, or utilizing any form of muscle memory to influence their reports.

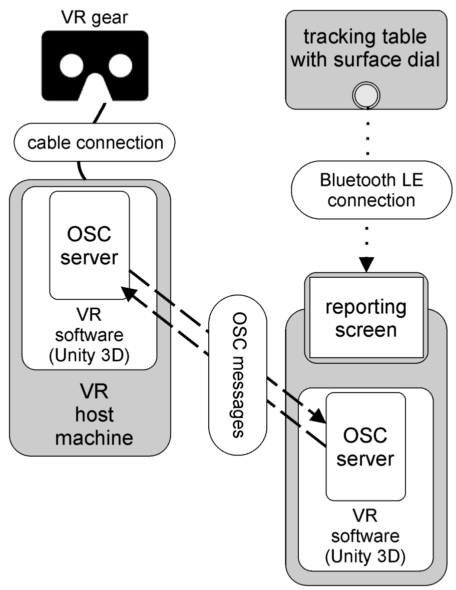


Figure 6.4: **Connection Schema between the tracking table, reporting screen, and VR host machine** *The Microsoft Surface Dial on the tracking table is connected via Bluetooth LE to the Microsoft Surface Studio Machine running the reporting screen. This machine exchanges OSC messages with the VR host machine, which runs the main VR simulation and is connected to the VR gear (HMD and controlers) via cable.*

6.3.4 Visual Aspects

Participants wore an HTC Vive HMD. The resolution of the HMD is 1080 x 1200 pixels per eye (2160 x 1200 pixels combined) for viewing the stereoscopic virtual environment. The field of view of the HMD is 100 horizontal degrees and 110 vertical degrees. The IVE was calibrated to render a carefully registered virtual model of the physical environment. The virtual model of the experimental room and apparatus were created to resemble the physical room and apparatus in terms of size, scale, and appearance. Fusion 360 and Maya were used to create an accurate virtual replica of the experimental apparatus and surrounding environment. The 3d models of dials, and other 3D printed elements, such as the tracking table's clamps, were used both to fabricate the physical artifacts, and in the virtual environment simulation, so that they dimensions and appearance were identical. The simulation was designed so that the virtual dials also had their textures carefully replicated so that users would visually perceive their rotation in the IVE. Figure 6.5 shows screen shots of the virtual environment, tracking table and reporting screen.

Figure 6.5: **Virtual models developed for this study** *a) Experimental room replicating the real experimental room. b) Reporting screen. c) Tracking table, d) Researcher GUI.*

6.3.5 Study Design

This study, depicted by Figure 6.6, has a hierarchical mixed design, with the predicted size of dials as dependent variable, and three independent variables:

1. **IV1**: *Session*, with two levels: *pretest*, and *post-test*.

2. **IV2**: *Feedback condition*, with two levels: *vision only* and *haptics only*.

3. **IV3**: *Divergence*, which is nested between IV1 and IV2, with two levels: *divergent minus* and *divergent plus*.

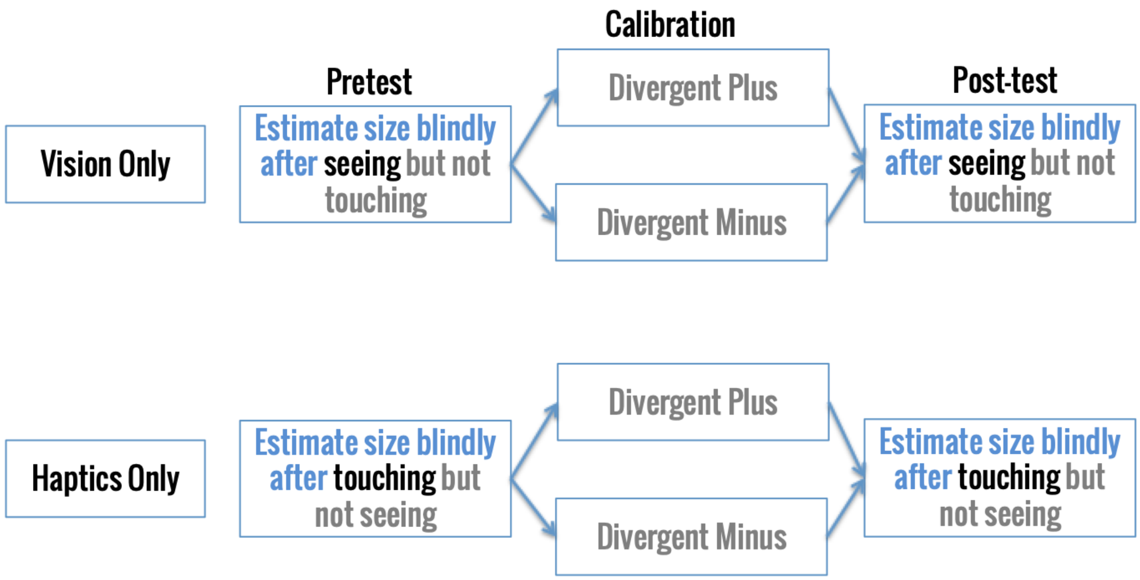


Figure 6.6: **Study Design.** *In this hierarchical mixed design study the independent variable Divergence is nested within the independent variables Feedback condition and Session.*

6.3.6 Tasks

The task involved participants estimating the diameter of knobs immediately after perceiving their sizes either by looking or physically interacting with them by touch.

During the pretest and post-test phases, participants were asked to either look or touch the dials presented to them (according to the feedback condition), followed by reporting their perceived sizes. During the calibration phase, participants were asked to both look and touch the dials to perceive their sizes. However, they were not asked to report on the perceived sizes in the calibration phase.

To get participants to interact with the dials more naturally, when touching the dials, participants were also asked to rotate the dials a couple of times as this action better characterizes interactions with tangible knobs in REs. The rotation of the dials was tracked, so that they would not just haptically perceive the rotation, but also see the rotation in the IVE.

6.3.7 Procedure

Participants were greeted and asked to read and sign a consent form upon arrival. They were verbally reminded that they could quit at any time. After consenting to participate in the study, participants filled out a demographics survey followed by the simulator sicknessquestionnaire (SSQ) [163]. The subjects were then randomly assigned to one of the two experimental feedback conditions. Next, I describe the procedural sequence for participants in the conditions.

1. After filling out the surveys, participants were asked to sit between the tracking table and the reporting screen. The instructions did not mention anything about the sizes of the dials, or how they would possibly be combined between their physical and virtual versions because we did not want to prime participants.

2. The interpupillary distance of the participant's eyes were measured with the smartphone app PD Meter [69]. In this process, a picture of the face of the participant was taken, and the interpupillary distance calculated by the app. The researcher would then use this information to calibrate the interpupillary distance setting in the HMD.

3. Users were asked to put on the HMDs and experience by vision and touch both the tracking table and the reporting screen for some moments. Users were than asked to face the reporting screen, and were instructed to follow the messages displayed by the reporting screen so they would know when to turn to the tracking table, and when to wait. They were also instructed on how to enter their estimated values for each trial.

4. Following this, participants began perceiving the size of dials, and entering their responses.

   During the pre-test phase, participants were expected to turn their chair between the position facing the tracking table and facing the reporting screen. At the beginning of a trial participants would face the reporting screen showing the message "Wait to begin next trial". Meanwhile, a researcher would place the appropriate dial in the tracking table (when appropriate) and click the "Start Trial" button on the VR host machine. Participants would then receive the message "Turn around to begin next trial" on the reporting screen. At this point, participants were instructed to turn to the tracking table, and take as long as desired examining the dial before reporting the estimated size, independently of the condition (vision only, or haptics only), most participants took anywhere between 5 and 10 seconds. In the haptic condition, participants were also requested to rotate the dials at least a few degrees. Briefly after, when participants indicated they had sufficiently perceived the dial, they were instructed to turn their chairs toward the reporting screen and report the size immediately after turning. With a virtual replica of the reporting screen (and other RE elements) displayed in VR, users would touch the physical reporting screen with their fingers, and visualize that action in VR, with the exception that we opted not to track hands (to avoid body-scaling effects). Once they estimated the size, they would press the message bar that read "Press to end trial". Upon pressing, the estimated size was recorded, and a new trial would begin with the message "Wait to begin next trial" being displayed to the participant once again.

5. After estimating the diameter of 48 randomly selected dials in the pretest phase (16 distinct dials three times), users were exposed to the calibration phase. During this phase, participants were asked to turn toward the tracking table from their original positions facing the reporting screen to both touch and look at the dials to perceive their sizes. However, they were not asked to report on the perceived sizes. When touching, they were also asked to rotate the dials a few degrees, as this action better characterizes interactions with tangible knobs in REs, instead of just touching them.

6. After experiencing (with vision and haptic stimuli) eight randomly selected combinations of (physical x virtual) dials three times, totaling 24 pairs, users would begin the post-test phase.

7. The procedure of the post-test phase was the same as the pretest phase.

8. After completing the post-test phase, participants filled out another instance of the SSQ [163], and the Presence Questionnaire [289], POMS [240], and Nasa TLX [142]. Their financial compensation was handed to them, and they were dismissed. Each participant took on average one hour to complete the experiment.

6.3.8 Data Collection

Apart from the survey responses, and reported estimated sizes for each trial, we also recorded simulation-based data like the position and orientation of the participant's HMD, the inputs received by the Microsoft Surface Dial in the tracking table, the movement (frame by frame) of the participants finger-touch on the reporting screen, and the moment both researchers and participants began and ended each trial by interacting with on-screen buttons. However, the analysis will focus users' predicted sizes of dials.

6.4 Results

6.4.1 Comparing pretest data between visual and haptic feedback

The analysis began by comparing pretest results between visual and haptic feedback to investigate RQ1. To evaluate the effect of visual versus haptic feedback on near field size perception of tangible objects in virtual reality, we first subjected the pretest size perception results to a multiple regression analysis [103]. This analysis is considered relevant as it directly quantifies the relationship between two continuous dependent and independent variables. Prior to conducting the multiple regression analysis, an analysis of standard residuals was carried out on the data to identify any outliers, which indicated that some of the outliers needed to be removed. Based on an analysis of standard residuals, after 15 samples were removed, the data contained no further outliers (Std. Residual Min = -2.25, Std. Residual Max = 2.00). Test to see if the data met the assumptions of collinearity indicated that multicollinearity was not a concern (Actual Knob Diameter, Tolerance = 1.0, VIF = 1.0; Condition, Tolerance = 1.0, VIF = 1.0). The data met the assumptions of independent errors (Durbin-Watson value = 0.44). The scatter plot of standardized residuals showed that the data met the assumptions of homogeneity of variance and linearity. The data also met the assumptions of non-zero variances.

A multiple regression was conducted to examine if feedback method (vision vs. haptics) and actual knob diameter predicted the estimated diameter (size) of the knobs. A significant regression equation was found $F(2, 486) = 332.57$, $p < 0.001$, with an R-squared= 0.58. Participants predicted knob diameter is equal to *-18.36 + 1.55 (Actual Knob Diameter) - 6.53 (Feedback Method)*, where feedback is coded as 1 for visual feedback and 0 for haptic feedback, and actual distance is measured in millimeters. The knobs predicted diameter increased by 1.55mm for each millimeter of the actual knob diameter. The knobs predicted diameter with visual feedback was -6.53mm less than that with haptic feedback. Both independent variables, actual knob size ($p < 0.001$) and feedback method ($p < 0.001$) were significant predictors of predicted knob diameter (size).

By condition, the linear regression equation for the predicted knob diameter in the visual feedback condition is equal to *-7.45mm + 1.26* x *actual knob size* (R-squared = 0.54). Whereas the linear regression equation for the predicted knob diameter in the haptic feedback condition is equal to *-35.68mm + 1.84* x *actual knob size* (R-squared = 0.62). Figure 6.7 shows the linear regression profiles of the participants performance in the visual and haptic feedback conditions from the pretest data.

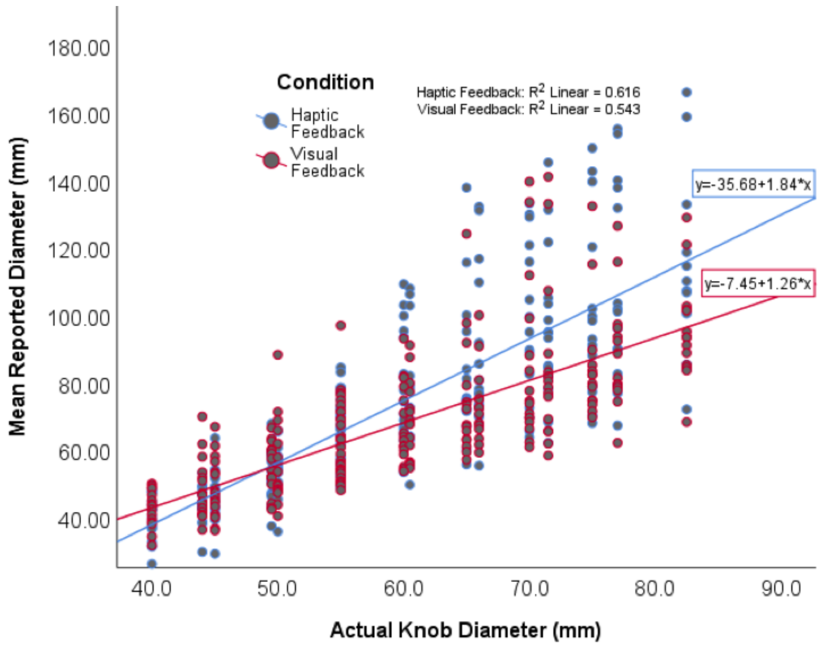


Figure 6.7: **Regression profiles** *Participant's performances in the visual and haptic feedback conditions.*

We also compared regression coefficients R-squared, slope and intercept systematically between the feedback conditions. We conducted an independent samples t-test in order to compare the R-squared, slopes and intercepts in the participants individual perceived diameter responses in the pretest session between the visual and haptic feedback conditions. However, we did not find any significant difference in these regression coefficients between the visual and haptic feedback condition on the pretest perceived knob size data.

6.4.2 Comparing condition, stimuli divergence, and session on knob size perception

To examine the effect of condition, positive and negative visuo-haptic divergence, and session on perceived diameter of the knob, we performed a complex multiple regression analysis. First, as was done in the previous subsection, an analysis of standardized residuals was conducted on the data to identify outliers, which indicated that 15 data points were over +3.5 standard residual error and were major outliers. Upon removing the outliers, the minimum standard residual in the data was -2.25 and the maximum standard residual was +2.95. Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (Feedback condition, Tolerance = 1.0, VIF = 1.0; Divergence, Tolerance = 1.0, VIF = 1.0; session, Tolerance = 1.0, VIF = 1.0; Actual Knob Diameter, Tolerance = 1.0, VIF = 1.0). The data met the assumptions of independent errors (Durbin-Watson value = 0.93). Finally, the histogram of standardized residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardized residuals, which showed that the data were close to the regression profile, and the data also met the assumptions of non-zero variances.

With the assumptions for multiple regression analysis verified, we next conducted a multiple regression analysis to examine if actual knob diameter, session (pretest vs. post-test), visuo-haptic divergence (positive vs. negative), and condition (vision vs. haptics) predicted reported knob diameter. A significant regression equation was found $F(4, 994) = 279.14$, $p < 0.001$, with an R-squared = 0.53. Predicted participants reported diameter is equal to *-27.47mm + 6.02* x *Condition 2.59* x *Divergence 1.78* x *Session + 1.55* x *Actual Knob Size*, where Condition is coded as 1 for visual feedback and 2 for haptic feedback, divergence is coded as +1 for divergent plus condition and -1 for divergent minus condition, session is coded as 1 for pretest and 2 for post-test, and actual knob diameter is measured in millimeters. The perceived knob size increased by 1.55 millimeters for every 1 millimeter of the actual knob size. The perceived knob size in the haptic feedback condition was 6.02 millimeters higher than that of the visual feedback condition. The predicted knob size in the plus visuo-haptic divergent condition was 2.59 millimeter less than the minus visuo-haptic divergent condition. The perceived knob size in the post-test session was 1.78 millimeters less than the post-test session. The independent variables feedback condition (vision vs. haptics) $p < 0.001$, divergence (plus vs. minus) $p < 0.001$, and actual knob size $p < 0.001$ were significant predictors of predicted knob size.

To evaluate the significant interaction effects, the independent variable of actual knob size was mean centered and the product with the other independent variables were computed. Then, the interaction terms were added to a second level of a hierarchical multiple regression model. The mean centered interaction terms were condition x centered actual knob diameter, divergence x centered actual knob diameter, session x centered actual knob diameter, condition x divergence, condition x session, divergence x session, condition x divergence x session, condition x divergence x centered actual knob diameter, condition x session x centered actual knob diameter, divergence x session x centered actual knob diameter, and finally the full interaction term condition x divergence x session x centered actual diameter. The hierarchical multiple regression model with the centered interaction terms was found to be significant, $F(15, 983) = 99.48$, $p < 0.001$, with an R-squared = 0.60 (with the change in R-squared of 0.07). The model revealed a significant condition x actual diameter interaction ($p = 0.001$), a significant condition x divergence interaction ($p = 0.003$), and a significant condition x divergence x actual diameter interaction ($p = 0.022$). The independent variable of session and other interaction terms were not significant predictors of the predicted perceived diameter.

To examine the interaction effects, we further examine the results through two simple linear regression profiles. One grouped by the overall (considering pre- and postest data) divergent x actual diameter interaction on predicted knob diameter in the visual feedback condition, and another regression profile grouped by the overall divergent x actual diameter interaction on predicted knob diameter in the haptic feedback condition. In the visual feedback only condition, the overall linear regression profile of the minus condition was perceived knob diameter is equal to *-3.58mm + 1.16* x *actual knob diameter* (R-squared = 0.52), and the overall linear regression profile of the plus condition was perceived knob diameter is equal to *-5.36mm + 1.28* x *actual knob diameter* (R-squared = 0.43), see Figure 6.8. However, interestingly in the haptic feedback only condition, the overall linear regression profile of the perceived knob diameter in the plus condition is equal to *-23.12mm + 1.51* x *actual knob diameter* (R-squared = 0.57), and the overall linear regression profile for the perceived knob diameter in the minus condition is equal to *-51.28mm + 2.22* x *actual knob diameter* (R-squared = 0.66), see Figure 6.9.

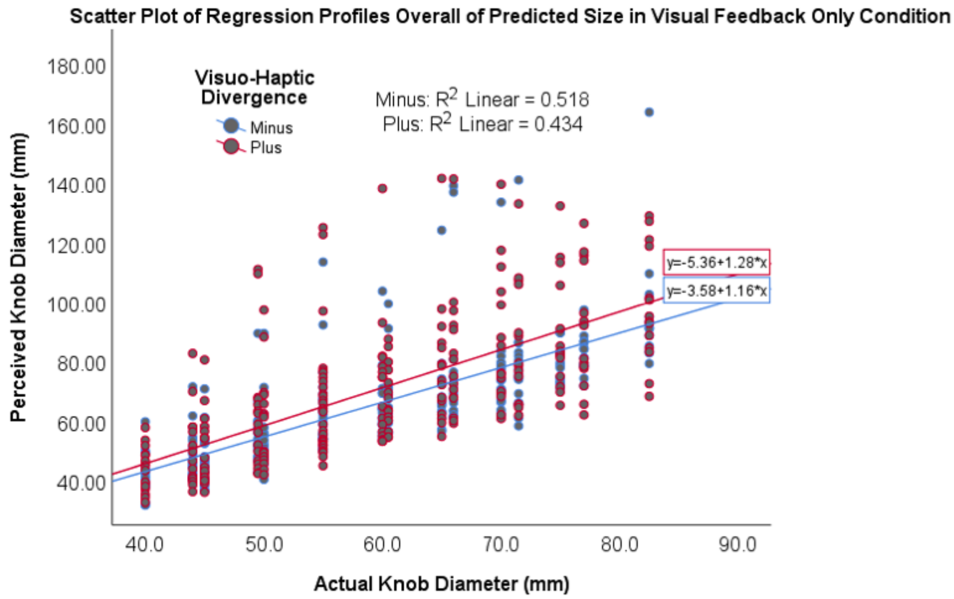


Figure 6.8: **Regression profiles** *The regression profiles of the perceived knob diameter by actual knob diameter in the minus and plus conditions overall in the visual feedback only condition.*

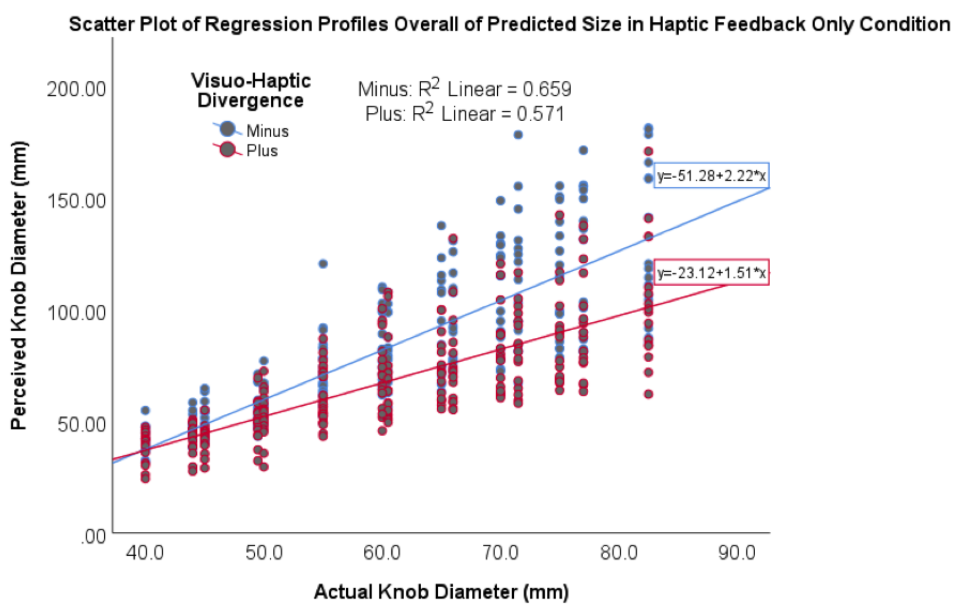


Figure 6.9: **Regression profiles** *The regression profiles of the perceived knob diameter by actual knob diameter in the minus and plus conditions overall in the haptic feedback only condition.*

We also examined the linear regression profiles of the participants perceived knob diameter to the actual knob diameter in the post-test session only in the plus and minus divergence conditions, separately in the visual and haptic feedback only conditions. In the visual feedback only session, the regression profile for the perceived knob size in the plus condition is equal to *-0.42mm + 1.19* x *actual knob diameter* (R-squared = 0.38), and the regression profile for the minus condition is equal to *-3.21mm + 1.16* x *actual knob diameter* (R-squared = 0.51), see Figure 6.10. In the haptic feedback only condition, the regression profile for the perceived knob diameter in the plus divergence condition is equal to *-18.07mm + 1.39* x *actual knob diameter* (R-squared = 0.54), and the regression profile for the minus condition is perceived diameter equal to *-41.88mm + 2.04* x *actual knob diameter* (R-squared = 0.64) see Figure 6.11.

The pattern of the overall and post-test results were very similar in that in the visual feedback only condition, the slope of the regression profiles of the plus condition is slightly higher than the minus condition. However, the difference between the plus and minus conditions is not very different overall.

The pattern of the overall and post-test results in the haptic only condition are different than the visual feedback only condition in that the slope of the minus condition is dramatically higher than the slop of the plus condition and performance seems to diverge drastically.

One similarity in both types of feedback conditions is that the participants seem to be more consistent in perceiving the knob diameter in the minus condition than in the plus condition, as evidenced by the R-squared values in the plus and minus divergence conditions overall.

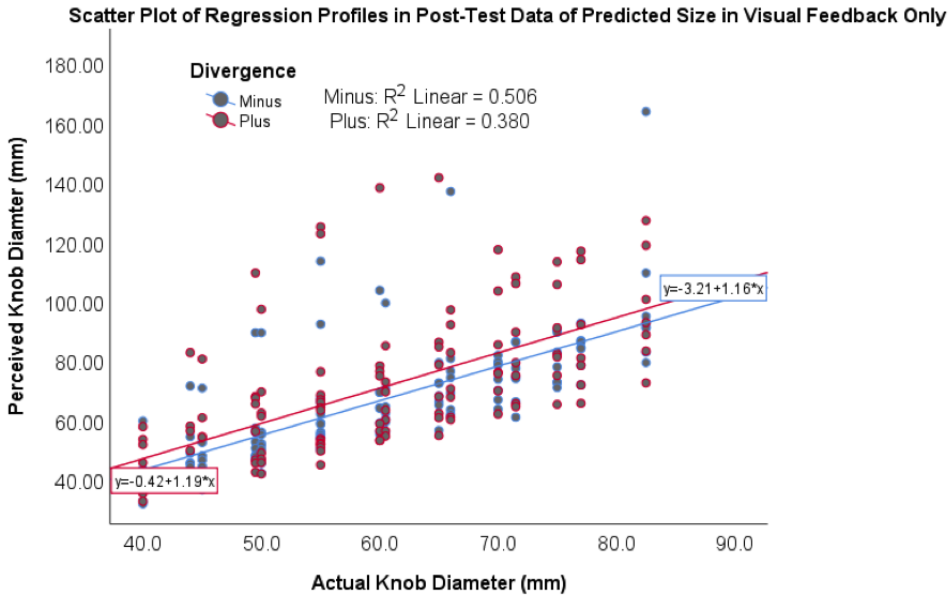


Figure 6.10: **Regression profiles** *Perceived knob diameter by actual knob diameter in the minus and plus conditions, and in the post-test data for the visual feedback only condition.*

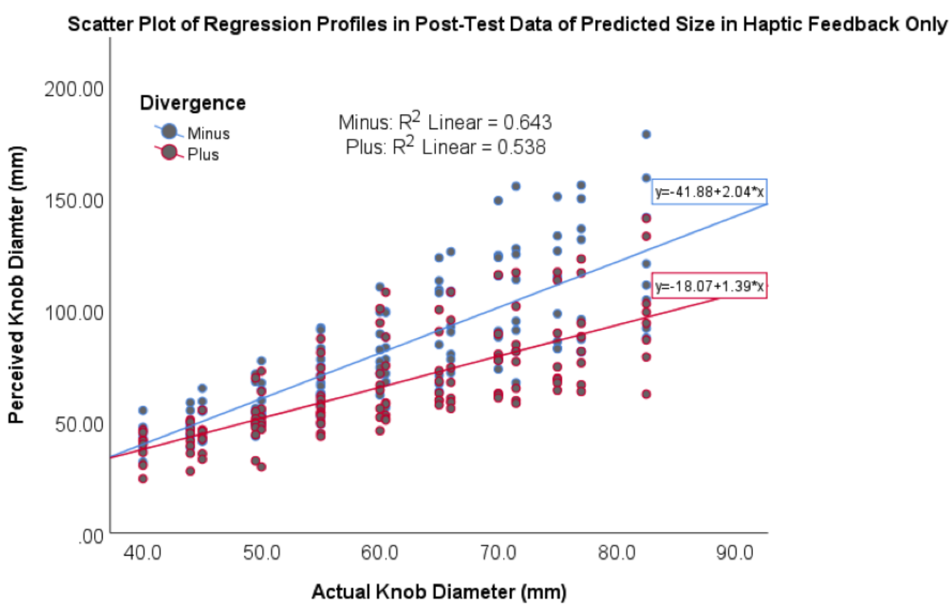


Figure 6.11: **Regression profiles** *Perceived knob diameter by actual knob diameter in the minus and plus conditions, and in the post-test data for the haptic feedback only condition.*

6.4.3 Examination of accuracy of perceived knob diameter

To examine if the accuracy of the perceived knob diameter over the experienced trial sets over time in the pretest and post-test sessions were affected by the type of information they received in the different feedback conditions (vision vs. haptics) and the visuo-haptic divergent information they received during calibration (plus vs. minus), we subjected the percent residual accuracy scores to a 12 (trialsets of 4 trials) x 2 (feedback condition) x 2 (session) x 2 (divergence) mixed model ANOVA analysis. The accuracy scores were calculated as:

(perceived knob size - actual knob size) / actual knob size + 100.

The ANOVA analysis revealed a significant main effect of trialsets $F(11, 308) = 14.32$, $p < 0.001$, partial $\eta^2 = 0.34$, a significant interaction effect of trialsets by condition $F(11, 308) = 2.61$, $p = 0.001$, partial $\eta^2 = 0.09$, and a trialsets by conditions by visuo-haptic divergence calibration interaction $F(11, 308) = 2.49$, $p = 0.005$, partial $\eta^2 = 0.082$.

Interestingly, we found that percentage residual errors of accuracy in perceiving the knob size gradually increased overall from one trial set to the next over time. In the visual feedback condition, the percent residual error scores were not significantly different between trial sets, see Figure 6.12. However, in the haptic feedback condition, errors in trial set 1 (M=0.55%, SD=14.89) were significantly lower than trial set 6 (M=26.6%, SD=24.27) p = 0.013, trial set 9 (M=32.9%, SD=33.21) p = 0.039, and trial set 12 (M=41.54%, SD=39.98) p = 0.026. Likewise, errors in trial set 2 (M=5.66%, SD=20.53) were significantly lower than trial set 6 p = 0.020, and trial set 12 p = 0.039. Also, error in trial set 3 (M=5.27%, SD=16.54) was significantly lower than trial set 6 p = 0.003, trial set 7 (M=25.05%, SD=28.94) p = 0.021, trial set 8 (M=27.01%, SD=30.08) p = 0.034, trial set 9 (M=32.91%, SD=33.21) p = 0.011, trial set 10 (M=38.1%, SD=39.5) p = 0.037, trial set 11 (M=37.0%, SD=38.2) p = 0.027 and trial set 12 (M=41.5%, SD=40) p = 0.013, see Figure 6.13.

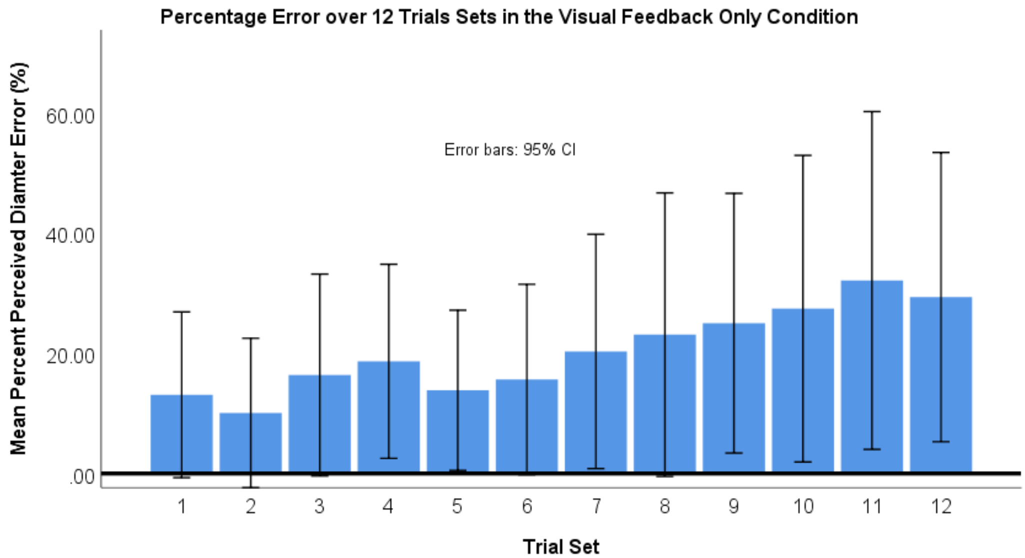


Figure 6.12: **Percentage Error** *Over 12 trial sets in the visual feedback only condition.*

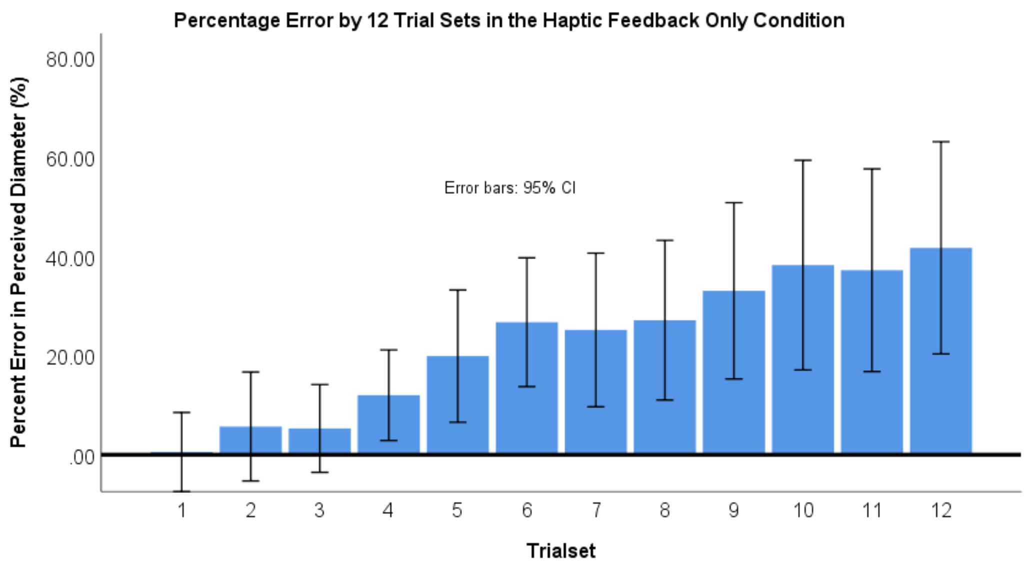


Figure 6.13: **Percentage Error** *Over 12 trial sets in the haptic feedback only condition.*

6.5 Discussion

Research in human perceptual-motor coupling has shown that the matching of visual, kinesthetic and proprioceptive information is important for calibrating perceptual information so that visuomotor tasks become and remain accurate. Many state-of-the art IVEs created for training users in near field visuo-motor tasks suffer from perceptual-motor limitations with respect to a decoupling of visual, kinesthetic and proprioceptive information due to technological issues such as optical distortions, tracking error and drift. [120]. Previous studies have shown that distance estimates became more accurate after a period of interaction with the environment, with accuracy improving from pretest to post-test [78, 94, 224].

I studied the effects of a visuo-haptic distortion during the prediction of size (diameter) of tangible knobs in the near field while users were immersed in an IVE. The results of this empirical evaluation show that both hypothesis (H1 and H2) are supported. In H1, it was hypothesized that there would be a difference between haptic feedback only and visual feedback only conditions in the perceived size of tangibles in VR. As described by subsection 6.4.1 and shown by figure 6.7, the perception of size is significantly different between the feedback conditions tested (visual and haptic). This supports our study design choice of studying haptic and visual feedback independently. In H2, it was hypothesized that calibration, with divergent physical and virtual sizes of knobs, would occur both in the haptic feedback only and in the vision only feedback conditions in the near-field perception of size of tangibles in VR. The results described in subsection 6.4.2 show that, considering post-test data, and taking into account the effects of calibration, in the haptic only condition the diameter of the knobs seem to be perceived differently in the two divergence conditions (plus and minus) as compared to vision only condition. This difference may be attributed to our unfamiliarity with perceiving sizes with haptic feedback only, and our familiarity to constantly making size judgements with vision only. Moreover, participants seem to be more consistent in perceiving the knob diameter in the minus divergence condition (as revealed by improvements in the r-squared values as well as changes in both the slopes of the regressions).

While the present results further our understanding of perceptual calibration of size in general, they also have important implications for the design of systems combining tangible and virtual reality interaction modalities. The results from this experiment support the notion that users of tangibles in virtual environments adapt their behavior to adjust to visual feedback that conflicts with their physical stimuli. This is an interesting finding, as it implies that users will likely be able to reasonably adapt to tangibles in virtual reality systems that may not have tightly corresponding visual and physical dimensions. This is of considerable interest to developers of hybrid systems combining tangibles and virtual reality since pre-existing physical knobs can potentially be re-utilized to represent size-mismatched virtual knobs, potentially reducing time (e.g. in the design, and fabrication steps, that may not be necessary), as well as cost due to re-utilization of materials.

Calibration is also potentially interesting to promote accessibility aspects of hybrid interfaces combining tangibles and virtual reality. It has been shown that current low-cost, consumer-grade fused deposition modeling (FDM) 3D printing equipment and supplies may not produce dimensionally accurate objects, in special the entry-level category [212]. Since calibration has been shown to modulate the perception of size while users are immersed in IVEs, the inherent accuracy limitations of the tangibles produced by low-cost 3D printing equipment may be compensated by calibration. As a result, developers with access limited to low-cost, entry-level FDM 3D printing equipment can still aspire to create effective systems combining tangibles and virtual reality interactions.

The results suggest that users perceive the size of tangibles differently in the haptic only and visual feedback only conditions. This may point to future research related to tangible interfaces developed specifically for the blind community. A search for the keyword "blind" within the proceedings for the Tangible and Embedded Interaction (TEI) conference in the ACM digital library [73] shows that this is a topic of relevance to the TEI community. Since the year 2010, 10 articles were published in relation to tangible user interface systems developed for the blind community, the majority within the past 4 years. The results from this study suggest paths to further understand how the blind community perceive the size of the tangibles within tangible systems developed for them. This could lead to interesting findings and potential changes in how tangible systems are developed for that community.

While this chapter explores combining tangibles and VR from a perception-action point of view, and may have direct implications not just to our understanding of near-field size perception in VR, but also to the design, fabrication, and potential re-usability of such systems, the apparatus developed for this study also embody several of the properties and characteristics discussed throughout this dissertation. For example, the apparatus developed embody interaction via the rotation of tangibles, mediation of information via passive and active elements, combinations of fabrication strategies and contrasting materials (such as wood and thermoplastic), combination of interaction modalities, reproducibility (of the dials), use of commodity devices, and inter-connectivity via several communication protocols such as Bluetooth, WIFI, and OSC messaging.

Considering the current work, this study demonstrates that such approaches are useful when developing research studies that involve physical artifacts. Beyond the current study, this points to future directions in which toward investigating the potential effects of contrasting materials, textures, weight, etc. to the perception of tangibles in IVEs and beyond.

Chapter 7

Exploring Other Representational Forms, Scales, and Modalities

"In my own work, I've tried to anticipate what's coming over the horizon, to hasten its arrival, and to apply it to people's lives in a meaningful way." Paul Allen

While most devices currently employ high resolution, high refresh-rate displays, a number of the devices discussed in this dissertation employ alternate means to mediate information. Taking as an example the knobs discussed in chapters 3 and 4, some mediate information passively (showing only passive text and icons), others mediate information actively (with LEDs and electronic paper displays), or employ hybrid approaches with embedded RFID tags. These approaches, however, have several limitations. "Naked" LEDs may be too bright (and sometimes uncomfortable) when directly aimed at human eyes, the size of Active Challenge Coins may limit the amount of information displayed, the size may also not allow information to be mediated beyond an arm's length distance, and LEDs and e-ink displays alone may not be capable of providing interactions as engaging as what (multitouch) screens are capable of.

To begin addressing these limitations, this chapter begins by describing strategies to enhance the comfort and legibility of tangibles that rely on LED illumination for information mediation. Then toward exploring alternatives for the fact that the typical size of challenge coins is often not sufficient to convey information (e.g.) across a room, we present Challenge Clocks: isomorphs of

Active Challenge Coins that embody larger form factors (approx. 12 inches diameter). Finally, we present initial prototypes of devices which embody many of the concepts of "digital shadows"[150]: we combine (6 to 12-inch) physical discs, and sometimes Active Challenge Coin cores, to cast "dital shadows" onto multitouch surfaces (such as tablets and larger multitouch surfaces) to produce interactive experiences that combine tangible and multitouch interaction, and create user experiences that can potentially be more engaging than each interaction modality considered alone.

7.1 Enhancing LED-based Information Meditation

To enhance the comfort when employing LEDs for information mediation on tangibles, we sought to employ two strategies: guiding and diffusing light (including combinations of both).

While we initially focused on investigating techniques to enhance the comfort of users, we stumbled upon a number of possibilities that could potentially be applied toward enhancing legibility. We next explore four approaches as described by Figure 7.1.

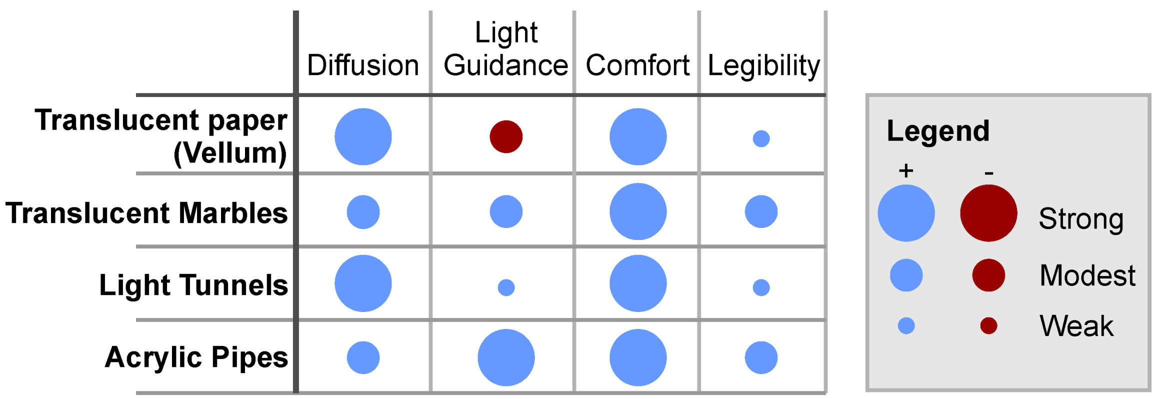


Figure 7.1: **Approaches toward enhancing the comfort and legibility of LED-based information mediation on tangibles:** *Each approach is classified in terms of diffusing or guiding light. They are also classified in terms of enhancing comfort and legibility.*

Translucent Paper (Vellum): After our initial experiences with LEDs on Active Challenge Coins, it became clear that "naked" LEDs were not comfortable to the human eyes. This led us to search for materials that would diffuse the direct light of LEDs. We achieve diffusion with regular (white) paper and with Vellum. Velllum is a translucent type of paper that may also be referred to as tracing paper, see-through paper or transparent paper. It refers to smooth, delicate paper you can see through. We have applied regular white paper and clear Vellum to diffuse light to avoid distorting the colors emitted by the LED lights. Figure 7.2 shows the envisionment of a tangible disc inspired by the book "The Moment of Lift" by Melinda Gates [71]. We apply diffusion of light with regular paper and Vellum to "illuminate" the dove in the center of the disc. In this envisioned tangible system, the color of the dove is used as feedback to the user, indicating which content option is selected. This approach would not be comfortable to users without diffusion of light, since the LEDs are aimed vertically upwards. However, as shown in figure 7.2c (taken from an early prototype), while this strategy generates an artifact tha may be considered asthetically pleasing, and comfortable to the human eyes, the diffusion effect also may have a negative effect on legibility, since individual LEDs may have their lights blended together as a side effect.

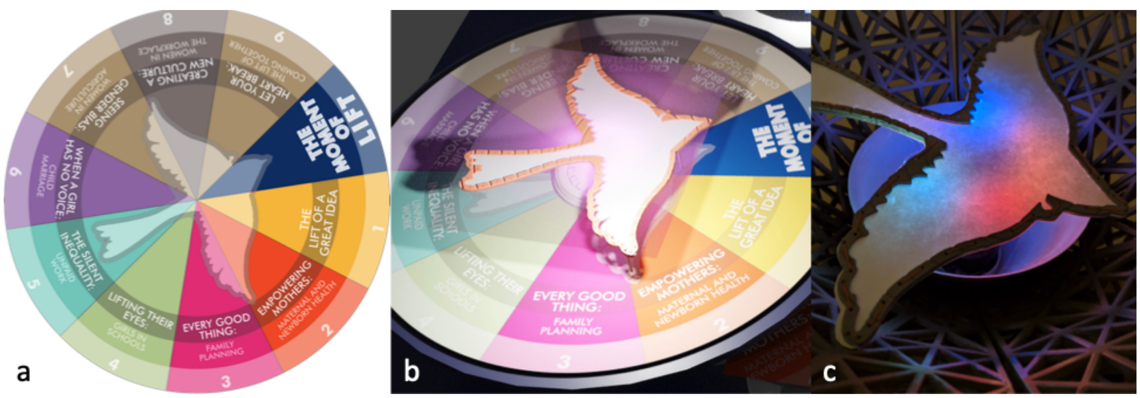


Figure 7.2: **Using diffusion of light to enhance visual comfort of LED illuminated artifacts:** *a) A 2D envisionment of a content disc inspired by the book "'The Moment of Lift" by Melinda Gates [71]. b) A 3D envisionment of the content disc featuring a dove that hovers above the disc. c) Physical prototype of the dove retro-illuminated with a 16-LED Neopixel ring with the colored lights being diffused by Vellum.*

Translucent Marbles: While paper and Vellum successfully diffused light, we sought to apply an approach that would not only make the LED lights comfortable to the human eyes, but would also provide a greater level of legibility. Toward this goal, we acquired a number of translucent plastic spheres or "marbles" and used them as "lenses" to diffuse the light of each LED individually. Starting with a regular Active Challenge Coin, we added a 3D printed top crown to the coin, embedding the translucent marbles on top of the LEDs.

Careful design allow the marbles to remain in place without the use of any form of glue or other adhesive, which could potentially distort, or alter the light. Figure 7.3 shows the envisioned and physical prototypes built. This approach allowed us not just to diffuse the light of each LED individually, with greater legibility in comparison to the previous approach, but also showed us that it was possible to "guide the light" by controlling the distance and position of the marbles. This inspired us to pursue the approaches discussed next to "'bend" or "guide" the light from LEDs.

Figure 7.3: **Using translucent marbles to diffuse light:** *a) Original Active Challenge Coin design, without any strategy to diffuse light. b and c) 3D envisionments of the Active Challenge Coin with translucent marbles for light diffusion. d) Early physical prototype of the Active Challenge coin with marbles. This prototype also shows Light Tunnels discussed next.*

Light Tunnels: Light tunnels consist of hollow physical structures that guide light by blocking and redirecting it. With this technique, we are able to redirect part of the light emitted by upward facing LEDs, (e.g.) downwards to illuminate the electronic paper display of

Active Challenge Coins. While this is and effective and simple approach, a major part of the light may get absorbed by the "tunnel" itself and get diffused, directly impacting legibility. Figure 7.4 shows an Active Challenge Coin inspired by the United Nations Sustainable Development Goals [74] with the light tunnel structure and the detail of an early prototype.

Figure 7.4: **Using Light Tunnels to guide light:** *a and b) Envisioned Active Challenge Coin inspired by the United Nations Sustainable Development Goals, with light tunnels. c) Early physical prototype of the Active Challenge coin with light tunnels.*

Light Pipes: With the development of light tunnels and the realization of its limitations, we sought to develop a technique that would allow us to have greater control over "bending" or "guiding" light, while also enhancing legibility by guiding the light of each LED individually.

During the development of illuminated content discs (further detailed later in this chapter), we faced the challenge of illuminating a disc with LED lights, while having a Microsoft Surface Dial positioned between the disc and the LED ring. This required the light emitted by the LEDs to "curve" around the Surface Dial. To achieve this effect, we built laser-cut light pipes out of acrylic sheets. These acrylic pieces are able to conduct the light from each LED up and around the Microsoft Surface Dial, all the way to the bottom surface of the disc.

While the LED lights at the end of the light pipes were comfortable to look at, and legible, the sides of the acrylic light pipes also became illuminated . Beyond the aesthetically pleasing visual effect, this also opened the perspective of employing the side-illumination as another channel for proving visual feedback to users. We implemented a pulsating pattern of the LED lights as feedback for user interaction with the discs, such as rotation. With the side-illuminated light pipes other people besides the user of the system can perceive when an action has been performed. This feature can be valuable when multiple users are cooperating and need some (visual) feedback to maintain awareness of each other's actions. Figure 7.5 shows the content discs and the light pipes developed.

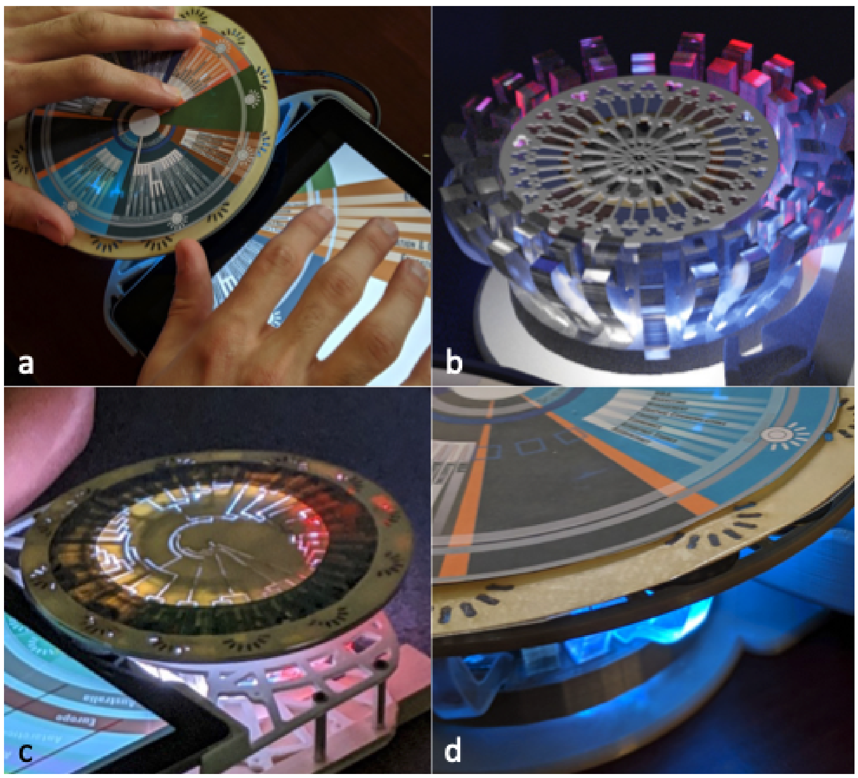


Figure 7.5: **Using Light Pipes to guide light:** *a) User interacting with the disc and the multitouch screen of a tablet. b) Envisionment of the light pipes transporting light from the bottom of the device to underneath the disc. c and d) Prototype of the light pipes illuminating the disc and the area around it.*

So far in this chapter, I have described a number of approaches to enhance information mediation with LEDs in tangible systems. Next, we will look at Challenge Clocks: isomorphs of Active Challenge Coins toward mediating information at a distance, such as across a room.

7.2 Developing Challenge Clocks

There are several limitations related to the scale and form of Active Challenge Coins. The small size (approx. 60 mm diameter) limits not just the amount of information that can be displayed, but also the distance from which users can perceive the information.

Toward exploring larger representational forms that would complement our ecology of tangible devices, we sought to develop an isomorph of Active Challenge Coins by using similar active components to mediate information, such as LED rings and e-ink displays. Where the Active Challenge Coins employ 16 to 24-LED rings and a single 2-inch e-ink display, Challenge Clocks employ 60-LED rings in combination with 8 larger (4-inch) e-ink displays.

To mediate information, we also applied several strategies to guide and diffuse light. We use 60 small mirrors (5 mm X 10 mm) to reflect the light emitted by the down facing LEDs onto horizontally mounted e-ink displays. Figure 7.6 shows details of the mirrors for guiding light.

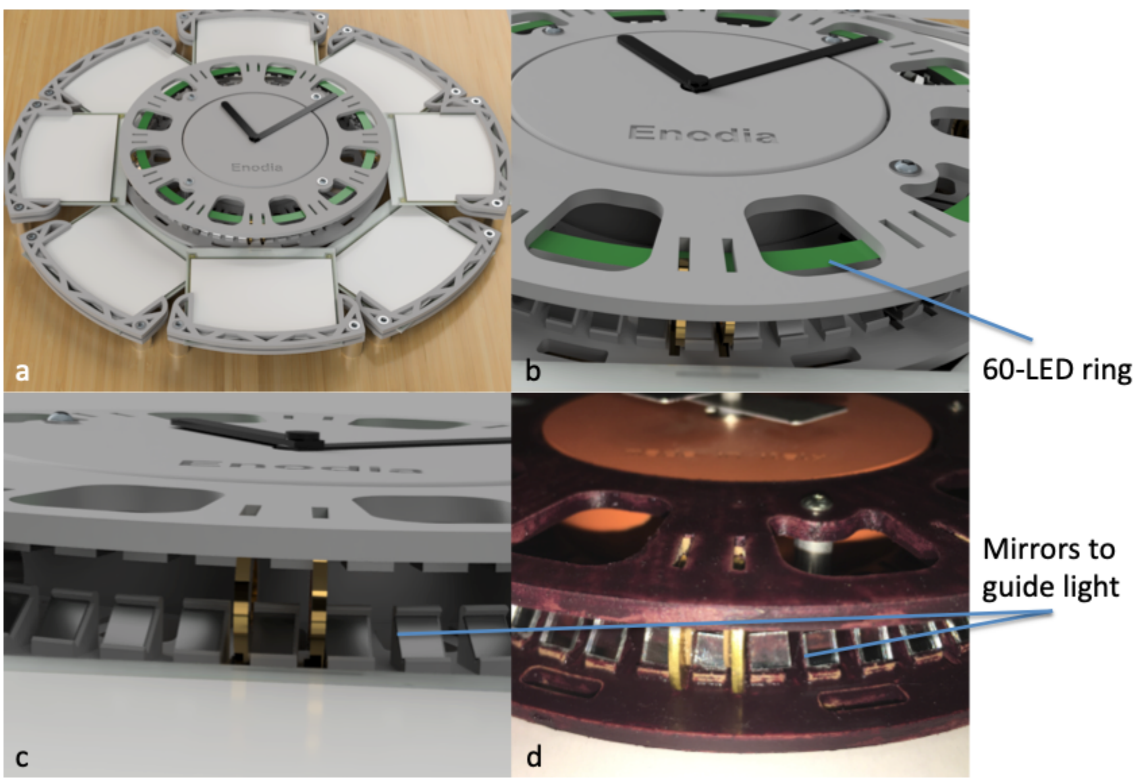


Figure 7.6: **Challenge Clocks employ small mirrors to guide and reflect light:** *a) 3D model of a Challenge Clock. b) Detail of the down-facing 60-LED ring. c and d) 60 small mirrors surround the Challenge Clock and reflect the light from the LEDs.*

Challenge Clocks were designed to mediate information when the user is both near and from a distance. From a distance, the user can perceive how each e-ink display is illuminated and can also perceive information by reading large icons displayed by the e-ink displays. When closer to the Challenge Clock (from approx. an arm's length), the user can read detailed information displayed by small icons and text. Next, we describe and illustrate an envisioned use-case, and how each strategy for mediating information is applied. Figure 7.7 shows the envisioned Challenge Clock in the use-case and an partially functional prototype.

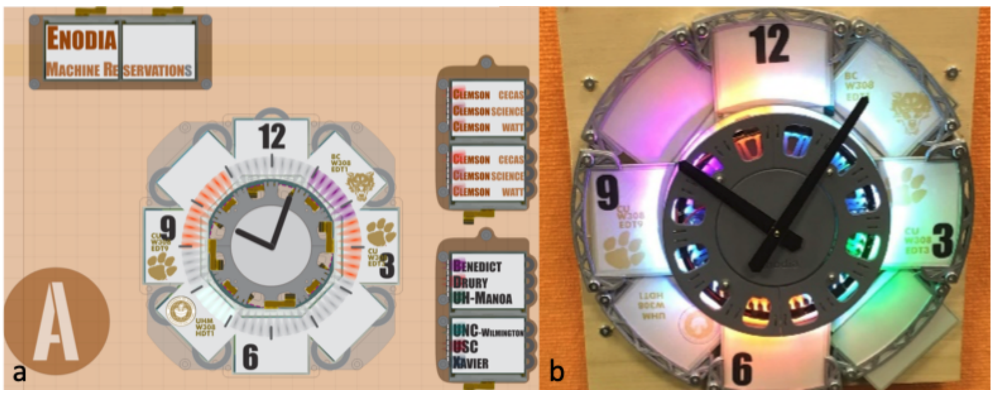


Figure 7.7: **Challenge Clock for Computer Cluster Allocation Scheduling:** *a) Envisioned interface for the Challenge Clock. b) Partially functional prototype of the interface displaying information both with e-ink displays and LED lights.*

In this envisioned scenario, Challenge Clocks display information about the usage and scheduling of high-performance computing nodes shared by a number of universities across the country. Toward mediating information that can be perceived from a distance, the Challenge Clock displays large icons representing each university on the e-ink displays and employ color-coded LED illumination onto these displays according to the time scheduled by teams from each university. Toward mediating information that can be perceived when users are close to the clock, the e-ink displays also show additional textual information and small icons. Next, we list several practical applications for these mediation strategies in the scenario proposed:

- An illuminated clock, regardless of the colors of the illumination, can easily communicate if the computing nodes are being used (or not). Considering the fact that computing nodes and clusters can cost several thousands to millions of dollars, and have life spams of less than 10 years in most cases, having a quick way to assess if such equipment is being used can be of great importance.

- The mirror-reflected lights and their colors can quickly communicate which university teams are occupying the computing nodes.
- The mirror-reflected lights can also indicate the general availability or occupation of the computing nodes, which can be used to judge if and when (e.g.) additional time can be reserved.
- Some additional detailed information can be obtained by approaching the clock and reading the text on the LED displays. Important to note that the clocks do not aim at replacing comprehensive dashboards or desktop interfaces for task scheduling.

With the Challenge Clocks, we explored isomorphs of Active Challenge Coins embodying a larger scale in a diverse representational form. We described several ways in which (small and large) icons and text, in combination with LED illumination can mediate information to be perceived both from a close distance and from across a room. In the next section, we describe another representational form and interaction modality that is inspired by and embodies several of the mediation strategies discussed in the previous sections.

7.3 Exploring Digital Shadows with Tangible Discs

Following the development of Challenge Clocks, we began to look for other like-forms and interaction paradigms that would provide users with more opportunities for interaction.

We drew inspiration from the concept of "digital shadows" described by Ishii and Ullmer [150] in which they apply the metaphor of light and shadow as interfaces to bridge the physical and virtual spaces. In our interpretation of "digital shadows", we envisioned a physical tangible disc mounted partially on top of a tablet with the physically illuminated disc casting a "digital shadow" onto the tablet. In this arrangement, the disc and the multitouch screen of a tablet are intimately connected, with the screen serving as an extension of the physical disc. Figure 7.8 shows some of the prototypes developed. The devices and discs were both piloted with young users and took part at demo sessions in early 2019.

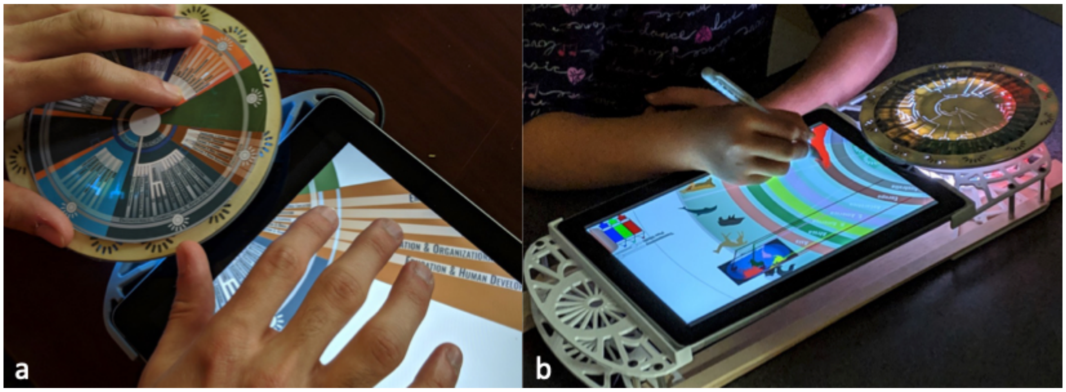


Figure 7.8: **Devices embodying "digital shadows" concepts:** *a) Device with disc developed with content related to Clemson University. b) Child interacts with pilot of the Mammals and continents edition.*

The devices are built from an combination of fabrication approaches and materials. For the body of the devices, we initial created a version combining 3D printed with soft wood, employing screws and other hardware for assembly. While the contrast of materials was attractive, a following version employed mostly 3D printed elements. These have less small parts (therefore safer for children) and were easier and faster to build. A similar approach was taken with discs. Some of them employ wood, others acrylic, and we also employ 3D printed elements to give them structural integrity and to connect the discs to the underlying Microsoft Surface Dials.

As described earlier in this chapter (Figure 7.5), we employed LED lights and light pipes as a way to illuminate the physical discs. Illumination and capacitive sensing in the discs are driven by WIFI-capable Arduino microprocessors connected to the tablets, and communicating via the exchange of OSC messages [293]. A Microsoft Surface Dial captures the rotation of the disc and communicates to the tablet via Bluetooth connection.

(Corel draw Diagram, fusion illustration)

Content-wise, we envisioned a number of diverse discs. Some examples are the "Moment of Lift" disc, the Mammals/Continents disc, and the Clemson University disc. Figure 7.9 shows the detail of some of the discs and interfaces developed.

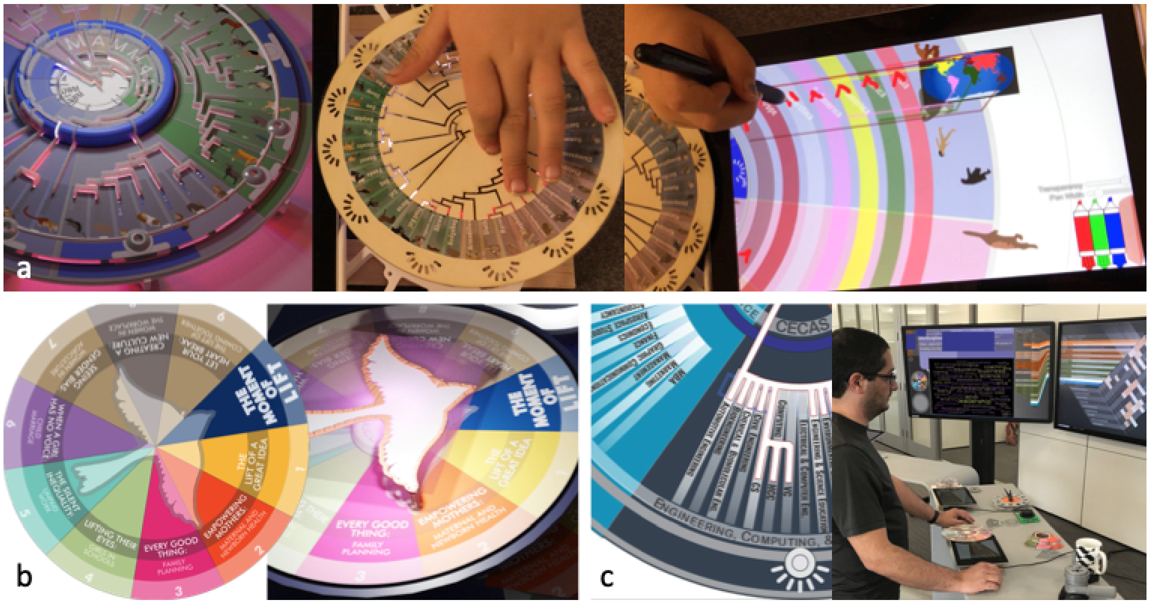


Figure 7.9: **Detail of several discs and interfaces developed:** *a) 3D envisionment of disc with Active Challenge Coin core, prototyped disc, and user interacting with Mammals/Continents interface and disc. b) "Moment of LIft" inspired disc (2D and 3D envisionments). c) Clemson University detail of disc and pilot present at an Watt Family Center event at Clemson University to a group of faculty in February 2019.*

To exemplify the interaction with the devices, we will describe the Mammals/Continents interface. This interface was inspired by Montessori Schools' activities in which children learn how to relate animals to the continents where they occur. This activity is typically taught without the use of any computational support. We aspired to develop a system that could potentially capture children's attention, generate engagement, and potentially positive learning outcomes (such as longer recall of information when compared to the traditional method). To this end, we designed shown in Figure 7.9a. The embodied interaction of rotating the discs, associated with the possibilities of illuminating the device with LEDs and light pipes, and the dynamic nature of the gestures and images displayed by the multitouch screens are the main factors that led us to propose this device. To truly verify our aspirations for this device, a careful empirical evaluation of this device in comparison to paper-only and tablet-only approaches have been conceptualized. However, such study is beyond the scope of this dissertation, and will be pursued as future work.

Several elements contribute to the legibility and comfort of "Digital Shadow" devices. The light pipes strategy adopted make the LED illumination comfortable to the eyes, the multitouch screens of the tablets complement the legibility of discs by adding high-definition, dynamic real-estate to the interface; Interaction is also complemented: where discs can only be rotated and capacitively touched, tablets support more advanced interactions (e.g. multitouch gestures). For larger real-estate, discs 12-inches can also be utilized and combined with larger tablets potentially enhancing both legibility and comfort. Finally, both right- and left-handed users can comfortably interact with the device by choosing which position for the discs suit them the most.

This chapter described and discussed a number of tangible devices and interfaces that embody representational forms, scales and interaction modalities beyond what had previously been presented. From previous challenges, especially with Active Challenge Coins, this chapter focused on strategies to enhance the comfort and legibility of tangibles. Beyond the focus of this chapter, the "Digital Shadow" devices described embody several of the properties and characteristics discussed throughout this dissertation, such as embodied interaction via the rotation of tangibles, mediation of information via passive and active elements, combinations of fabrication strategies and contrasting materials, combination of interaction modalities, reproducibility, use of commodity devices, and inter-connectivity via several communication protocols such as Bluetooth, WIFI, and OSC messaging. Based on these remarks, we see the "digital shadow" devices as strongly supporting the concepts put forward by this dissertation, in which computationally-mediated systems consisting of hybrids of complimentary representational forms, scales, and mediation modalities can be more legible and actionable than non-hybrid ones.

Chapter 8

Discussion and Conclusions

The mediation of digital information remains dominated by screen-based approaches. We have become accustomed to an immense variety of sizes, aspect ratios, and variations upon "screens". In combination with general purpose input devices, they form the predominant paradigm in human-computer interaction.

Over the past decades, several limitations have been recognized in relation to graphical user interfaces (GUI) in general and the WIMP (windows-icon-mouse-pointer) in particular, such as the "input"and "output" asymmetry [263]. This has led to a number of research and commercial efforts aimed at overcoming limitations and better linking the physical and virtual worlds. Among those are virtual and augmented reality, and tangible interaction. However, especially in the tangible interactions field, research has focused on tangible interaction alone or in comparison to other modalities.

This thesis has worked to identify and articulate systems combining a number of cyberphysical representational forms, scales and interaction modalities, which were presented and explored regarding their design and fabrication approaches, reproducibility, and legibility. The argument has been on the basis of two main combinations of interaction modalities explored by the thesis projects: combining tangible and multi-touch interaction and combining tangible and virtual reality interaction.

I have explored laser cutting and 3D printing approaches, including combinations of both, and applied a number of materials such as acrylic, thermoplastic, metal, and wood. Toward reproducibility, the processes and components considered were selected due to their wide availability, relative affordability, and accessibility to a large number of populations and age groups.

Supported by the LAVA heuristics, a number of the hybrid systems developed were demonstrated to have enhanced legibility. Legibility was also explored for systems employing very-low pixel count, and low power consumption, such as those equipped with LED rings and e-ink displays. I explored a number of strategies to enhance legibility when using (LED) light, and isomorphic variations on the scale and form of active challenge coins, such as discs, and active challenge clocks. I have also explored the engagement of users with the Entrada poster platform, and performed an empirical evaluation of the effects of calibration on the near-field size perception of tangibles in immersive virtual environments, with potential implications on the design and fabrication of tangibles systems combining tangibles and virtual reality.

8.0.1 Implications of the Pragmatic Approaches

Tangible interaction in general, and tangible user interfaces in particular are usually either prototypes, which may never be commercialized and reach users in-the-wild, or are commercially available at costs that limit their reach. Two examples are the Reactable [53], and other special-purpose tabletops for tangible interaction [70]. The dissemination of such systems is, therefore, challenging in first-world countries, and even more difficult in third-world countries.

The term "digital divide" characterizes any uneven distribution in the access to, use of, or impact of information and communication technologies between any number of distinct groups [75]. In particular, some of the causes for the digital divide in Brazil, which are representative of a number of other countries, are: inefficiencies in resource allocation, a culture of heavy bureaucracy, lagging higher education, and, most relevant for this discussion, low penetration of new technologies [111].

Which begs the question: "How to develop tangible user interfaces, including hybrids there of, toward bridging the digital divide?"

There are three main aspects to bridging the digital divide:

- **Access:** which is related to availability, affordability and design for inclusion,
- **Adoption:** by designing and building systems which are relevant to the context of the audience and support digital literacy efforts, and
- **Application:** of systems that are geared toward workforce development, and education.

The work described in this thesis has been based on three man pragmatic approaches:

- Creating reproducible devices
- Employing commodity devices
- Re-imagining vintage and niche devices

These pragmatic approaches can be directly linked to the access facet for bridging the digital divide. Figure 8.1 shows a table with the relationship between them.

The work toward designing and fabricating reproducible tangible dials employs components and fabrication approaches that can be considered widely available. Laser-cutting, and especially 3d printing have achieved reasonable popularity with low equipment costs, availability of consumer-grade devices, and the dissemination of 3D printing (and sometimes laser-cutting) resources in maker spaces and public libraries. The ability to fabricate the dials also meant that I could effectively design them "for inclusion", with continuous consideration for maximizing which age groups and skills were necessary to reproduce them.

A number of the systems developed, such as the Entrada poster platform, are based on commercially available commodity deices, such as tablets. They strong on the availability and affordability aspects, but moderate on "design for inclusion". This score is achieved with the 3d printed and laser-cut elements that augment the tablets in the systems developed.

Several of the systems developed employ commodity devices, such as the Microsoft Surface Dials. These devices were originally developed for niche applications involving digital artists, such as Adobe Photoshop, and users of other image and video editing software. By employing the Microsoft Surface Dials in these projects, I have demonstrated its potential as a tangible interface tool that can potentially be used by a larger audience, beyond what was possibly initially intended by its engineers. I have also begun to explore new uses and applications for vintage devices, such as old cellphones, that have a short life-span, and are usually discarded after a couple of years of use. By augmenting them with some of the strategies presented in this dissertation, and creating interfaces that utilize them, we can aspire to extend their life-spams and utility beyond what was originally intended, and potentially use them as tools to bridge the digital divide.

Based on these remarks, I expect that this work has begun to show some paths toward closing the digital divide not just in Brazil, which is my home country, but also in so many other countries still working to solve this problem.

Figure 8.1: **Pragmatic approaches and the Access facet for bridging the digital divide** *This dissertation has employed pragmatic approaches that are related to reducing and bridging the digital divide, which may support the dissemination of tangible and hybrid interfaces.*

8.0.2 Limitations and challenges

The hybrid systems, and the design and fabrication approaches described in this thesis work provide a promising and effective means for people to interact with computational systems, beyond the screen-dominated landscape which is predominant today.

While this has provided a major motivation for this thesis, it also begs consideration of the limitations and challenges faced by the thesis approach. Many of these issues have been considered within the discussion section of each chapter, among other places; this section extends and summarizes these earlier discussions.

Fabrication approaches: This thesis has mainly employed two fabrication approaches: laser cutting and 3d printing. While these technologies were not chosen at random, with the former representing a subtractive technology, and the latter representing an additive technology, both popular, and for the most part, affordable and accessible, there are several other fabrication approaches that were not explored by this dissertation work that can potentially have transformative impacts. For example, 2D CNC routers can, in several occasions, substitute laser cutters. Although with limitations, such machines may even be more practical and yield better results than laser cutters when cutting paper. In a number of situations, legibility could have been further explored with paper elements produced with 2D CNC routers. Several other technologies could also have been employed. Recently, a number of consumer-grade 4-axis 3D CNC routers have been released. Such machines are usually able to sculpt metal pieces, such as aluminum, that could potentially complement the 3d printing approaches explored in this work. It is my expectation that the approaches discussed in this dissertation can be generalizable to other current and future fabrication technologies.

Choices of materials and sensory responses elicited: Related to the limited number of fabrication approaches is the limited number of materials employed in the fabrication of the devices created. While I've tried to diversify the materials employed resorting to paper, acrylic of several types, metal, thermoplastic, rubber, etc. Other materials may have an important role in future research exploring hybrid systems. For example, chapter 6 explores the effects of calibration on the near-field size perception of tangible knobs. All dials fabricated for that experiment were produced with gray PLA thermoplastic, and all dials weigh a few grams. Inspired by previous research related to the color of tangibles [181], other materials, textures, and even the weight of dials may affect the perception of size. These variations may also have implications to user experience, sense of presence and immersion when combining tangible and virtual reality interaction.

Optimization of commercially available devices: Demonstrating the feasibility of hybrid systems combining fabricated, and (sometimes enhanced) commercially available devices is one of the objectives of this dissertation work. However, there are limitations, and challenges, to this approach. The commercially available devices may be more reliable, and sometimes less costly them building your own, however, in several cases API's for calibration and customization have limited functionality, which limit or add complexity to employing such devices in hybrid systems. For example, in chapter 5, figure 5.4, I illustrate the architecture necessary to loosely connect multiple Microsoft Surface Dials to a host system running a virtual reality environment. While this is not inherently a limitation of the device, but instead a side-effect of pushing it beyond its original intended use, it's important to note that this approach has such challenges that may require time, patience, expertise, and creativity to overcome.

Designing for seamless integration of hybrid interaction modalities: One challenge derived from designing hybrid systems involving tangibles is to achieve seamless integration between modes of interaction involving no tangible interaction at all, and tangible interaction only. I have explored this challenge in chapter 4, with the Entrada poster platform, with users allowed to use tablets without any tangibles (multi-touch only), and to use only tangibles to interact with the content displayed by large vertical displays. Such systems inherently produce software and hardware requirements that are beyond those of systems employing single modes of interaction. It is my expectation that the benefits of these approaches for the user experience will surpass the possible costs and complexity currently associated with them.

Novelty effect of tangibles: A challenge related to researching novel systems in general, and those involving tangible interaction in particular, is the "novelty effect" [167] that such systems may elicit on users or participants. To reduce this effect when developing the Entrada poster platform the students involved with the project were exposed to system (and the tangibles) for at least 10 hours. While this strategy was effective with the content creators in reducing (or eliminating) the novelty effect on them, we did not have a similar strategy for the general audience that interacted with the system. Researchers investigating such systems have to be especially aware of the impacts of the novelty effect on the data they collect when investigating such systems.

8.0.3 Contributions

In supporting the thesis statement, the dissertation has made a number of specific contributions. These include:

1. *Identification and characterization of hybrid representational forms, scales, and modalities as an approach toward more legible and actionable cyberphysical systems.*

2. *Realization and demonstration of a number of prototyped cyberphysical systems, which embody multiple complimentary representational forms, scales, and mediation modalities.*

3. *Entrada Poster Platform*
4. *Empirical evaluation of the effects of calibration on the near-field size perception of tangibles in immersive virtual reality environments*
5. *Proposal and realization of strategies to enhance the legibility of tangible artifacts based on low-count LED illumination and electronic paper displays for information mediation*
6. *Proposal and realization of a framework for fabricating and deploying cyberphysical systems geared toward out-of-the-lab encounters.*

8.1 Future Work

This dissertation work has explored several design and fabrication approaches in the creation of a number of reproducible devices of several forms and scales, which were applied to computationally mediated systems that provide users with hybrid interaction modalities. A number of paths toward future work have be identified. Next, I list several of them:

Explore other design and fabrication approaches: The investigation of other design and fabrication approaches may lead to several future work opportunities related to the topics discussed in this work. New design and fabrication approaches may lead to opportunities in reproducibility aspects of the devices created, and allow the exploration of other representational forms that are currently not viable. Beyond form, other fabrication approaches may allow for the exploration of new materials and textures, which may, in turn, create opportunities for enhancing the legibility of future systems and devices.

Further explore combining tangibles and virtual reality: Others have explored combining tangibles and virtual reality [294, 188, 136]. However, this work presents alternative approaches, both by exploring design and fabrication aspects of combining tangibles and VR, and by exploring perception aspects. It is my expectation that further work will explore other aspects related to the perception of tangibles in VR, especially in relation to higher perceptual constructs, such as affordances.

Explore other hybrid systems: The further exploration of hybrid systems may elicit user interaction modalities that may be more efficient, or effective. However, perhaps more importantly, future work exploring new hybrid approaches of tangible interaction and other modalities may develop systems providing enhanced user experiences. In this path, new strategies for enhanced legibility and actionability may be discovered, advancing the concepts developed in this dissertation.

8.2 Closing Remarks

This dissertation has developed several computationally mediated systems which combine interaction modalities such as tangible and multi-touch and tangible and virtual reality into hybrid cyberphysical systems that are potentially more legible and actionable than any of them considered alone. Several of the systems created are based on the class of tangibles populated by cylinders, knobs, and dials, both as building blocks, and as representatives of other artifacts for tangible interaction.

Toward developing strategies accessible to several groups of researchers and practitioners, I have explored designs and fabrication approaches that favor reproducibility, and the utilization of commercially available commodity devices "as-is", as well as augmented versions. Supported by the LAVA heuristics, I have explored legibility and actionability aspects of a number of hybrid systems, and proposed several strategies for increasing legibility, especially for systems employing low pixel count LEDs and electronic paper displays to mediate information. I have also explored legibility aspects of isomorphs of active challenge coins of different scales, and implications to their legibility and affordances. I have developed the Entrada poster platform and explored design and engagement aspects of hybrid systems combing tangible and multi-touch interaction. I have performed an empirical evaluation of the effects of calibration on the near-field size perception of tangibles while users are immersed in virtual reality, with potential implications to how tangibles are designed and fabricated in hybrid systems combining tangibles and VR.

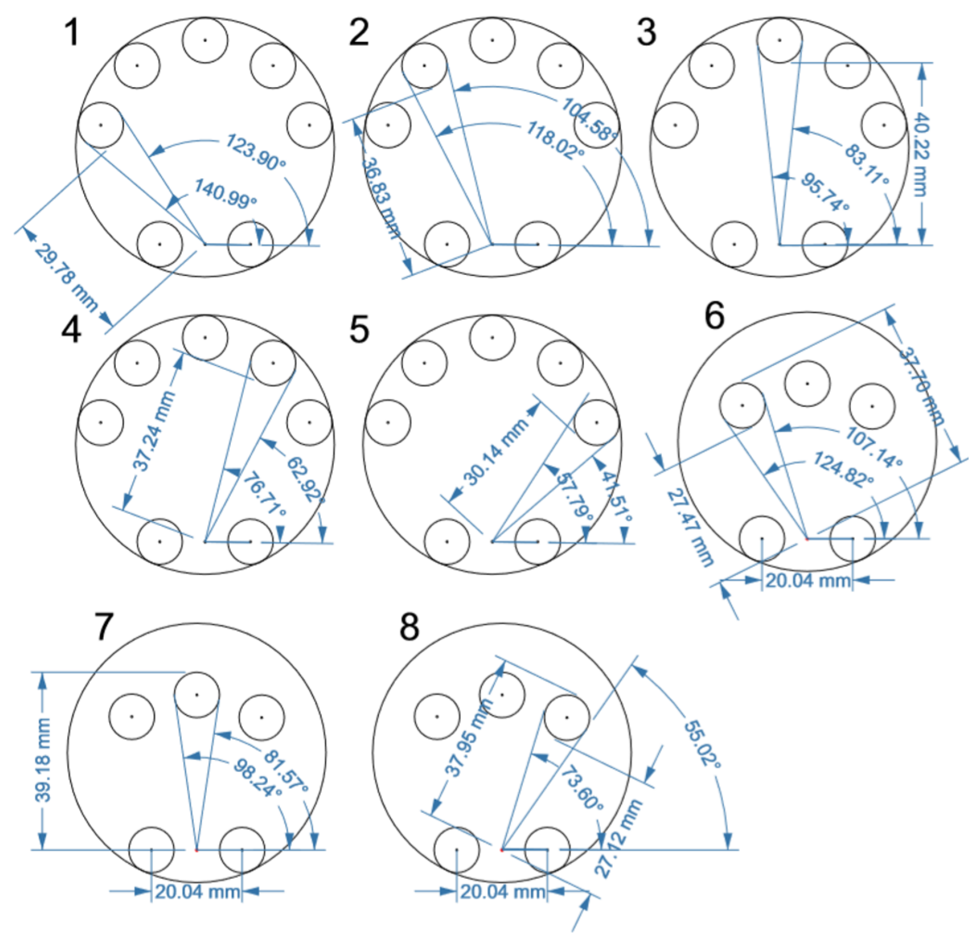
I hope that this dissertation work can inspire others to further study design, fabrication, usability, and user-experience aspects of hybrid computationally mediated systems, and perhaps more importantly, create and explore paths toward future interaction paradigms that are less dependent on screen-based interactions alone. I hope it shows a path toward systems that incorporate multiple representational forms, scales, and interaction modalities that cater to several of our innate perceptual and sensory channels, and may create more wholesome and engaging user experiences.

Appendices

Appendix A Three touch-point patterns for capacitively sensing tangible knobs

What follows is a template for touch-point patterns for tangible knobs for capacitive multi-touch screens. The patterns describe triangles, which can be identified by underlying software and provide identification, position and orientation of the knobs.

The template below describes eight distinct ids. While higher numbers of distinct ids can be achieved, this arrangement has been proven to be reliable. Higher number of ids may require a combination with other forms of identification (e.g. NFC tagging), or a larger radius for the tokens. The template presented can be applied to several fabrication approaches, such as a template for laser cutting, or 3D printing.



Appendix B Design and fabrication templates for laser cut knobs

The design and fabrication template for laser cut knobs is a document which contains drawings for the parts which have to be laser cut, and engraved. The document defines the type of suggested material (e.g. acrylic), and its thickness. The document also describes each of the parts which must be purchased, such as metallic rivets, nuts, and screws.

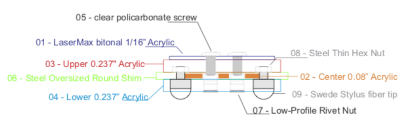
Diagrams of the assembly process and assembly instructions can be found, and are intended to support the users in the fabrication and assembly process of their own knobs. In its original version, drawings from the PDF file can be copied to vector-oriented programs (e.g. CorelDraw!, or Adobe Illustrator) and saved directly to laser cutter interfaces for production.

Next, we appended a scaled-down version of the 10-page template document.

TryKnob Design Template - TDT01

The images below depict one Knob after fabrication and assembly:

Technical Design

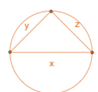


Template Details

This template is composed of 15 uniquely identifiable knob designs to be used with the TryKnob system.

In this template, all three sides of the triangle described by the pads that touch the capacitive screen may vary from one ID to the next.

The next pages of this document contain the designs for each component of the Knobs.



Number of distinct IDs: 15

Accuracy: 99%

Fabrication methods

The designs are intended for fabrication with laser cut machines, purchased parts and manual assembly.

Knobs are composed of nine distinct parts, four are laser cut pieces, the others must be purchased.

Parts and part numbers are described in Page 02.

Laser cutting conventions

Cutting lines
***R:* 255**
***G:* 0**
***B:* 0**

All lines have a stroke weight of 0.01mm

Vector stroke engraving
***R:* 0**
***G:* 0**
***B:* 255**

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

Acrylic materials referenced in this document may be exchanged by other materials, such as wood.

Parts and Part Numbers

Laser Cut Parts:

01 - LaserMax bitonal 1/16" Acrylic:

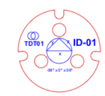
Top faceplate of the knob. Can be customized to fit different project scenarious

Page 3 - Labeled version
Page 4 - Unlabeled

02 - Center 0.08" Acrylic:

Center acrylic piece. Holds the pads in contact with the external Shim.

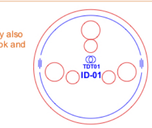
Page 5 - Labeled version
Page 6 - Unlabeled



03 - Upper 0.237" Acrylic:

Top body part of the Knob. Determines its general color. May also be built of wood or other material of choice to change the look and feel of the knob.

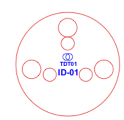
Page 7 - Labeled version
Page 8 - Unlabeled



04 - Lower 0.237" Acrylic:

Lower body part of the Knob. May also be built of wood or other material of choice to change the look and feel of the knob.

Page 9 - Labeled version
Page 10 - Unlabeled

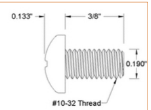


Parts and Part Numbers

Purchased Parts:

05 - Clear Polycarbonate Screw:

Pan Head Phillips
10-32 Thread
3/8" Length



Part Number: 93140A175
*Part Number from http://www.mcmaster.com

06 - Steel Oversized Round Shim:

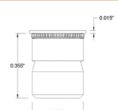
This piece must conduct electricity in order for the Knobs to work with capacitive surfaces.

0.134" Thick
1-3/4" Internal Diameter
2-1/2" Outer Diameter

Part Number: 97063A147
*Part Number from http://www.mcmaster.com

07 - Low-Profile Rivet Nut:

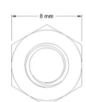
Cadmium-Plated Aluminum
10-32 Internal Thread
.355" Long



Part Number: 98560A176
*Part Number from http://www.mcmaster.com

08 - Steel Thin Hex Nut:

Zinc Plated
M5x0.8 Thread Size
8mm Wide
2.7mm High



Part Number: 90695A037
*Part Number from http://www.mcmaster.com

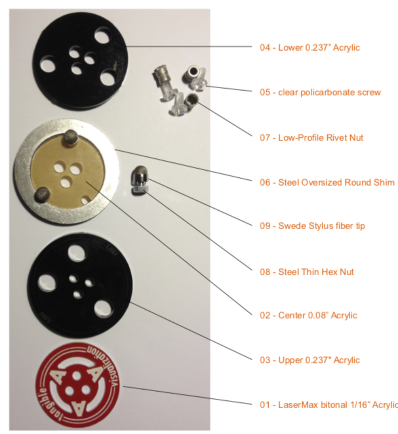
Parts and Part Numbers

Purchased Parts:

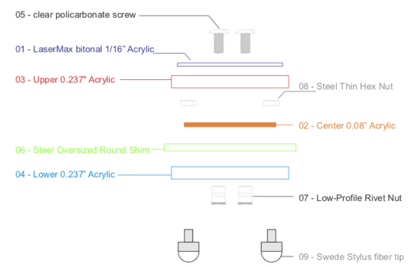
09 - Replacement Fiber Tips for The Friendly Swede®:

hybrid fiber/rubber design - tips have conductive coating
that is precise and sensitive
Compatible with capacitive touch screens

Purchase from www.amazon.com



Assembly Schematics



Assembly Instructions:

1 - Holding piece 06 (Steel Oversized Round Shim) and piece 02 (Center 0.08" Acrylic) screw them together with piece 09 (Swede Stylus fiber tip) and piece 08 (Steel Thin Hex Nut).

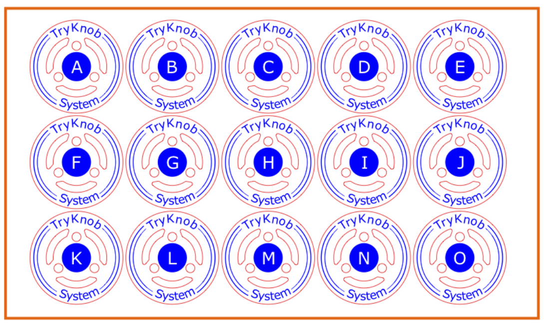
2 - Hold the pieces from step 1 with the printed infomation in readable position, set piece 03 (Upper 0.237" Acrylic) over it and piece 01 (LaserMax bitonal 1/16" Acrylic), both with printed information in readable position.

3 - Position piece 04 (Lower 0.237" Acrylic), with printed information facing down, below the piece from step 1.

4 - Insert pieces 07 (Low-profile Rivet Nut)

5 - Insert and screw piece 05 (clear policarbonate screw)

page 02



page 03

01 - LaserMax bitonal 1/16" Acrylic: (Labeled version)

01 - LaserMax bitonal 1/16" Acrylic:

Top faceplate of the knob. Can be customized to fit different project scenarios

Face plates are customized with Letters and Numbers as examples of possible cutomizations.

Laser cutting conventions

Cutting lines
R: **255**
G: **0**
B: **0**

All lines have a stroke weight of 0.01mm

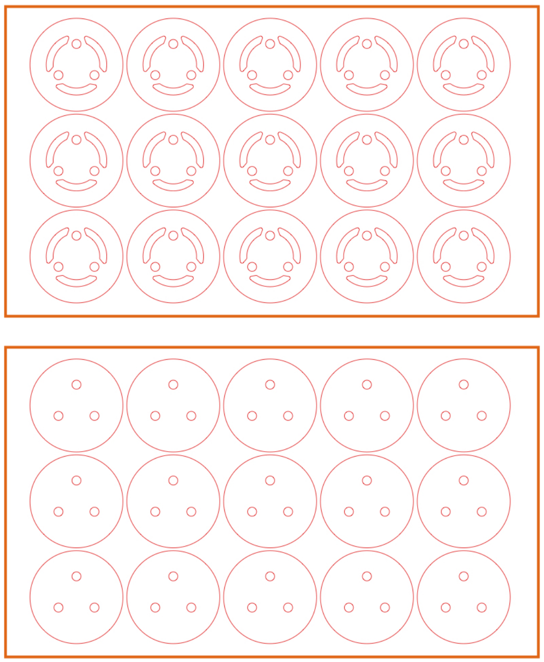
Vector stroke engraving
R: **0**
G: **0**
B: **255**

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (this page) or the Unlabeled version (next page).

Only objects inside the box to the left must be laser cut.



01 - LaserMax bitonal 1/16” Acrylic: (Unlabeled version)

01 - LaserMax bitonal 1/16” Acrylic:

Top faceplate of the knob. Can be customized to fit different project scenarious

Page:

Laser cutting conventions

Cutting lines
R: **255**
G: **0**
B: **0**

All lines have a stroke weight of 0.01mm

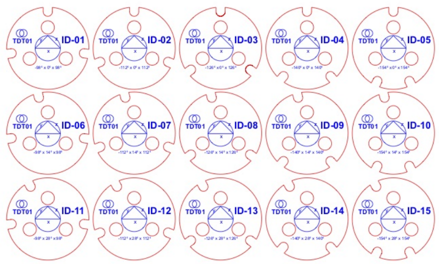
Vector stroke engraving
R: **0**
G: **0**
B: **255**

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (previous page) or the Unlabeled version (this page).

Only objects inside the box to the left must be laser cut.



page 05

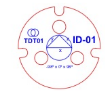
02 - Center 0.08” Acrylic: (Labeled version)

Each piece is labeled with:

- Template number: TDT01

- Id of the piece: ID-NN

- Coordinates of the slots for the conductive pads:
Ex. -48° x 0° x 48° means that the slot at the top is at 0°, and the others are both at a 48° angle.



Laser cutting conventions

Cutting lines
***R:* 255**
***G:* 0**
***B:* 0**

All lines have a stroke weight of 0.01mm

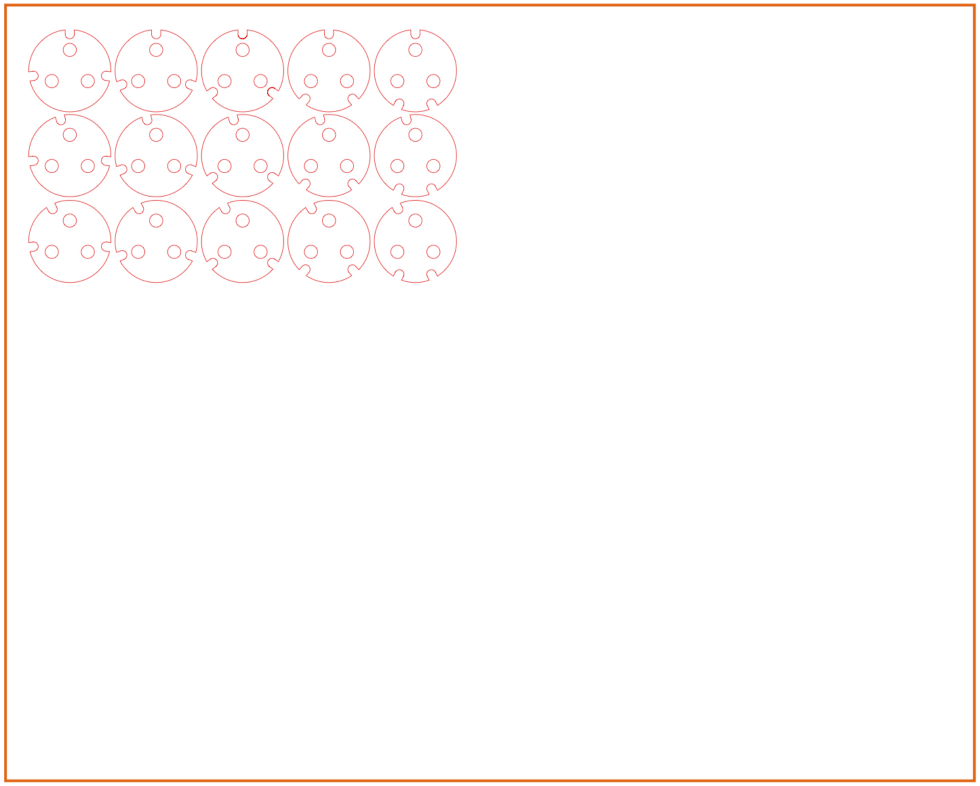
Vector stroke engraving
***R:* 0**
***G:* 0**
***B:* 255**

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

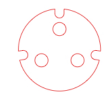
Either the Labeled version (this page) or the Unlabeled version (next page).

Only objects inside the box to the left must be laser cut.



02 - Center 0.08” Acrylic: (Unlabeled version)

This version has no labels. It is suitable to use this version when fabricating translucid versions of the Knobs.



Laser cutting conventions

Cutting lines
R: 255
G: 0
B: 0

All lines have a stroke weight of 0.01mm

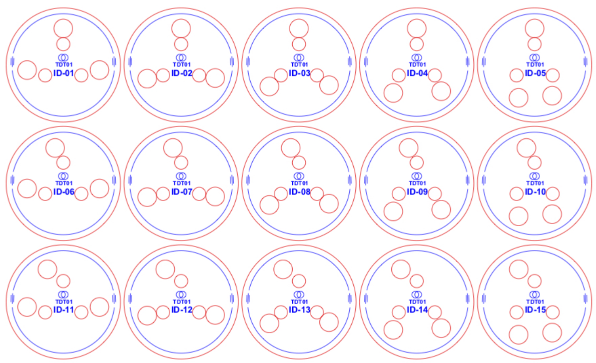
Vector stroke engraving
R: 0
G: 0
B: 255

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (previous page) or the Unlabeled version (this page).

Only objects inside the box to the left must be laser cut.



page 07

03 - Upper 0.237” Acrylic: (Labeled version)

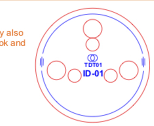
03 - Upper 0.237” Acrylic:

Top body part of the Knob. Determines its general color. May also be built of wood or other material of choice to change the look and feel of the knob.

Each piece is labeled with:

- Template number: TDT01

- Id of the piece: ID-NN.



Laser cutting conventions

Cutting lines

R: **255**
G: **0**
B: **0**

All lines have a stroke weight of 0.01mm

Vector stroke engraving

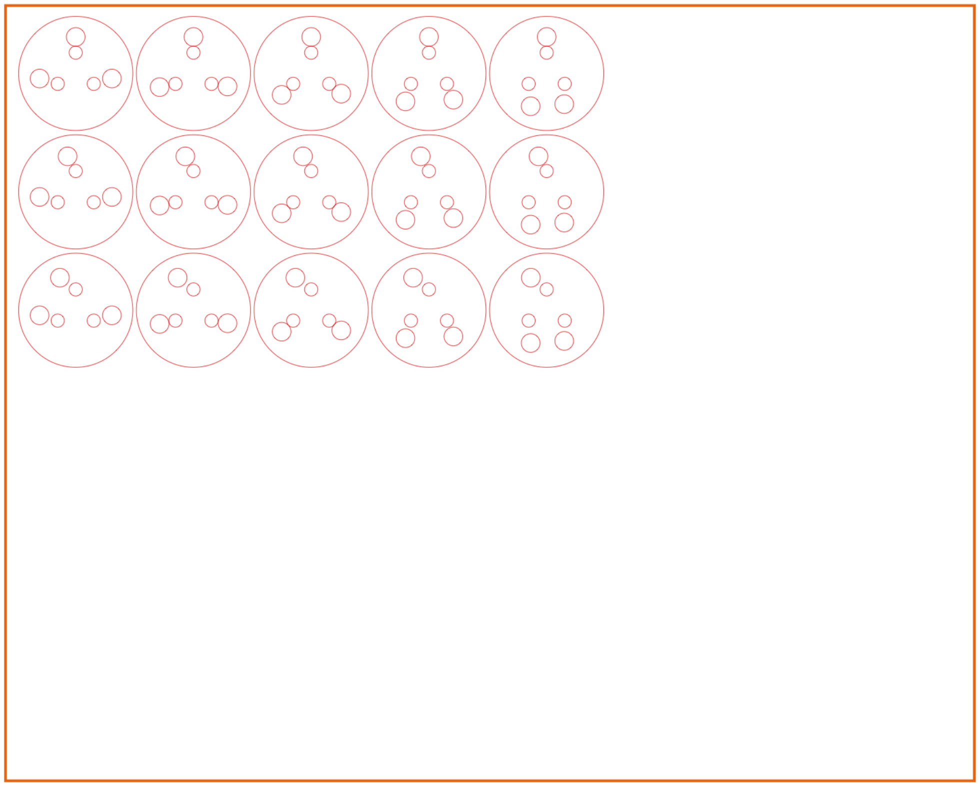
R: **0**
G: **0**
B: **255**

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (this page) or the Unlabeled version (next page).

Only objects inside the box to the left must be laser cut.

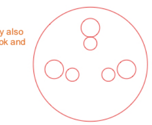


page 08

03 - Upper 0.237” Acrylic:
(Unlabeled version)

03 - Upper 0.237” Acrylic:

Top body part of the Knob. Determines its general color. May also be built of wood or other material of choice to change the look and feel of the knob.



Laser cutting conventions

Cutting lines

R: 255
G: 0
B: 0

All lines have a stroke weight of 0.01mm

Vector stroke engraving

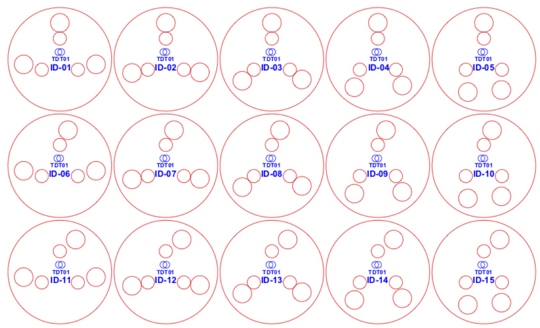
R: 0
G: 0
B: 255

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (previous page) or the Unlabeled version (this page).

Only objects inside the box to the left must be laser cut.



page 09

04 - Lower 0.237" Acrylic:
(Labeled version)

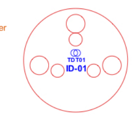
04 - Lower 0.237" Acrylic:

Lower body part of the Knob. May also be built of wood or other material of choice to change the look and feel of the knob.

Each piece is labeled with:

- Template number: TDT01

- Id of the piece: ID-NN.



Laser cutting conventions

Cutting lines
R: 255
G: 0
B: 0

All lines have a stroke weight of 0.01mm

Vector stroke engraving
R: 0
G: 0
B: 255

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

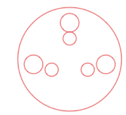
Either the Labeled version (this page) or the Unlabeled version (next page).

Only objects inside the box to the left must be laser cut.

04 - Lower 0.237" Acrylic:
(Unlabeled version)

04 - Lower 0.237" Acrylic:

Lower body part of the Knob. May also be built of wood or other material of choice to change the look and feel of the knob.



Laser cutting conventions

Cutting lines
R: 255
G: 0
B: 0

All lines have a stroke weight of 0.01mm

Vector stroke engraving
R: 0
G: 0
B: 255

The conventions adopted in this template must be changed to suit the particular laser cut machine in use.

For this piece, it is only necessary to laser cut one set, labeled or unlabeled.

Either the Labeled version (previous page) or the Unlabeled version (this page).

Only objects inside the box to the left must be laser cut.

Appendix C Token identification code

The following is part of a Python library for the identification of passive capacitive knobs on top of multi-touch surfaces.

The triangle described by the three touch points in the knobs is identified by measuring the distance and angle between the mid-point of the base of the triangle, and the top point.

```
import kivy

from kivy.app           import App
from kivy.properties    import *
from kivy.uix.label     import Label
from math               import acos,cos,sin
from math               import sqrt
from math               import pi
from math               import atan2,degrees, radians

class PatternId():
  DEBUG = False
  pc = None
  pb = None
  pa = None
  paUid = None
  pbUid = None
  pcUid = None
  minLength = 0
  minSide = (None, None)
  midPoint = (None, None)
  topPoint = None
  topPointUid = None
  distMidTop = None
  token_angle = None


  def build(self):
    pass
    #self.buildPoints()
    #self.findTokenId(self.pa, self.pb, self.pc)
```

```
def findTokenId(self, dic_points, points):
  # This function finds the smaller side of a triangle
  # Rotates the triangle so that smaller side is the base
  # Finds the mid-point of the smaller side
  # Finds the distance and angle between the mid-point and
  # the third (top-point) of the triangle
  # Compares distance and angle to determine the ID of the token
  # prints  points
  pa = dic_points[0]
  pb = dic_points[1]
  pc = dic_points[2]

  self.paUid = points[0].uid
  self.pbUid = points[1].uid
  self.pcUid = points[2].uid

  self.findMinLength(pa, pb, pc)
  #Adjust angle, rotate points
  if self.DEBUG: print "Original minSide: " + str(self.minSide)
  angle = self.findAngle(self.minSide[1], self.minSide[0])
  if self.DEBUG: print "original angle: " + str(angle)
  self.token_angle = angle
  if angle < 0:
      angle = angle + 360
  if self.DEBUG: print "angle: " + str(angle)
  if self.DEBUG: print "rotation pivot: " + str(self.minSide[1])
  #Rotate to determine id
  nmin = self.rotate(self.minSide[1], self.minSide[0], radians(360-angle))
  self.minSide = (nmin, self.minSide[1])
  if self.DEBUG: print "normalized minSide: " + str(self.minSide)
  self.topPoint = self.rotate(self.minSide[1], self.topPoint, radians(360-angle))
  if self.DEBUG: print "topPoint: " + str(self.topPoint)

  if self.topPoint[1] < nmin[1]:
    nmin = self.rotate(self.minSide[1], self.minSide[0], radians(180))
    self.minSide = (nmin, self.minSide[1])
    if self.DEBUG: print "180 rotate normalized minSide: " + str(self.minSide)
    self.topPoint = self.rotate(self.minSide[1], self.topPoint, radians(180))
    if self.DEBUG: print "180 rotate topPoint: " + str(self.topPoint)
```

```
    self.midPoint = self.findMidPoint(self.minSide[0], self.minSide[1])
    if self.DEBUG: print "midPoint: " + str(self.midPoint)
    self.distMidTop = self.findLength(self.midPoint, self.topPoint)
    if self.DEBUG: print "distMidTop: " + str(self.distMidTop)
    # Find angle between midpoint and top point
    idAngle = self.findAngle(self.midPoint, self.topPoint)
    if self.DEBUG: print "idAngle: " + str(idAngle)

    tokenId = self.findId(idAngle, self.distMidTop)
    if self.DEBUG: print "tokenId: " + str(tokenId)
    return tokenId

  def buildPoints(self):
    #Creates three points
    #Used for testing purposes only
    self.pc = [-525.928, 7.876]
    self.pb = [-553.876, 17.318]
    self.pa = [-529.491, -11.842]

  def findMinLength(self, pa, pb, pc):
    # Finds the side of minimum length given three points (triangle)

    l1 = self.findLength(pa, pb)
    l2 = self.findLength(pb, pc)
    l3 = self.findLength(pc, pa)

    if l1 < l2 and l1 < l3:
      self.minSide = (pa,pb)
      self.topPoint = pc
      self.topPointUid = self.pcUid
      self.minLength = l1
    elif l2 < l1 and l2 < l3:
      self.minSide = (pb, pc)
      self.topPoint = pa
      self.topPointUid = self.paUid
      self.minLength = l2
    else:
      self.minSide = (pc,pa)
```

```
    self.topPoint = pb
    self.topPointUid = self.pbUid
    self.minLength = l3

def findLength(self, pi, pj):
  # Find length between two points
  x = abs(pi[0]-pj[0])
  y = abs(pi[1]-pj[1])
  length = sqrt((x*x)+(y*y))
  return length

def findAngle(self, p1, p2):
  # Find the angle between two points
  xDiff = p2[0] - p1[0]
  yDiff = p2[1] - p1[1]
  return degrees(atan2(yDiff, xDiff))

def rotate(self, origin, point, angle):
  #Rotates a point counterclockwise by a given angle around a given origin.
  #The angle should be given in radians.

  ox, oy = origin
  px, py = point

  qx = ox + cos(angle) * (px - ox) - sin(angle) * (py - oy)
  qy = oy + sin(angle) * (px - ox) + cos(angle) * (py - oy)
  return [qx, qy]

def findMidPoint(self, pa, pb):
  # Finds the mid-point between two points
  return (pa[0]+pb[0])/2, (pa[1]+pb[1])/2

def findId(self, idAngle, distMidTop):
  # Compares angles and distances to determine the id of a token
  # if an id cannot be determined it returns zero

  tokenId = 0
  if idAngle <= 140.99 and idAngle >= 123.90:
    if distMidTop >= 29.9:
```

```
        tokenId = 1
    if idAngle <= 118.02 and idAngle >= 104.58:
      if distMidTop >= 36.8:
        tokenId = 2
    if idAngle <= 95.74 and idAngle >= 81.00:
      if distMidTop >= 151:
        tokenId = 3
    if idAngle <= 76.71 and idAngle >= 62.92:

      if distMidTop >= 37.2:
        tokenId = 4
    if idAngle <= 57.79 and idAngle >= 41.51:
      if distMidTop >= 30.1:
        tokenId = 5
    if idAngle <= 124.82 and idAngle >= 107.14:
      if distMidTop >= 27.4 and distMidTop <= 37.0:
        tokenId = 6
    if idAngle <= 95.74 and idAngle >= 81.00:
      if distMidTop <= 39.18:
        tokenId = 7
    if idAngle <= 73.6 and idAngle >= 55.02:

      if distMidTop >= 27.12 and distMidTop <= 37.9:
        tokenId = 8
    return tokenId

  def getTokenAngle(self):
    # Returns the angle of the identified token
    return self.token_angle

  def getTopPointUid(self):
    return self.topPointUid

  def clearTopPointUid(self):
    self.topPointUid = None
knobPatternId.py
Displaying knobPatternId.py.
```

Appendix D Moral dilemma project – description and milestones

CPSC 6110 Project Proposal: Moral Dilemma

Group 8: Jessica Baron, James Dominic, Alexandre Siqueira, Michael Wooten

Date: February 8th, 2017

Introduction

What people say they would do may not necessarily be the actions they actually follow through with, given a particular situation. This concept has been analyzed through psychological research concerning decisions in moral and ethical dilemmas, such as the Trolley Problem, where a person must decide to allow a trolley continue on its path and kill five people or purposely alter the path of a trolley and kill one person but save the five others [1]. The goal of this project is to test this idea through a virtual reality scenario in which a user has to face a similar moral dilemma and make a decision.

In order to accurately analyze users' decisions in the simulation, the virtual experience must strongly exhibit presence. The developers plan to invoke presence through cues such as the sound of breathing through speakers as if it is the user's own breath; interactability, especially through physical tokens to control virtual machines and moveable foam objects representing 3D virtual props; and some virtual agent interaction. Several previous studies have exercised the same task of posing a moral dilemma [2]. One study is a VR experience, similar to the goals of this project, is an adaptation of the Trolley Problem where instead the user makes a decision to save one person or five people from a shooter [3]. Another entails witnessing racial discrimination [4]. The latter project focuses more on social presence than the project for this course will.

System Design

- **Equipment**: The project will be created for the HTC Vive and use its hardware. In addition, several "lighthouse" sensors will be produced and used in conjunction with physical devices to create real-world interactive devices for the virtual world [5]. These devices will include some form of object analogous to debris and one or two dials or valves that the user/player will interact with from the virtual world and physically manipulate in the real world. The dials will represent a two part method for opening and closing a doorway. Later in the simulation, these will be critical for the moral dilemma. In addition, the other object will be used as debris that must be physically removed from the scene.

- **Basic Scenario**: Upon starting the simulation, the user finds him-/herself in a room inside of a chemical plant, alone in the immediate space. There is some idle time where the user can observe the surroundings. The user is then prompted via a voice through a speaker to open a gate. This task introduces a gate-opening interaction to the user, a mechanism that will be a part of the decision the user will have to make later in the scenario. Following about a minute after the user successfully opens the gate, an explosion shudders the building. The user will begin to feel a sense of confusion and panic, and visual cues in the environment will lead him/her into a hallway. The hallway will suddenly go dark and disorient the user, and after several confusing moments, more visual cues will gear the user's attention towards the second room. In this room, the user will encounter characters who are critical to the moral dilemma of the scenario, and environmental cues will let the user know that there is not much time left for escape. One of these characters may be physically impaired and call for the user's help, and another may be too frightened to run out of the plant on his/her own. The user will have to make decisions on who to help (or not to help), considering the dwindling time left of survival.

- **User Interaction and Tasks**: There are three main categories of interaction: virtual objects, physical objects and virtual agents. Interaction with virtual objects include moving objects or debris on the scenario. Physical objects are related to knobs or tokens that are tracked in the 3D space and physical objects that will simulate debris, also tracked in the 3D space. Two virtual agents will be build, one for each "trapped" character in the scene.

- **Virtual and Physical Environments**: The virtual space the simulation takes place in will consist of two main rooms, the pre-explosion room and the moral dilemma room, along with the connecting hallway. The two rooms will consume the same exact 3D space but will appear to be different areas due to the change of assets within that space, triggered by the entrance into and exit from the connecting corridor. The user will be restraint to an open physical area about 10x10 square feet, most of it which will act as both rooms. The connecting corridor will be a smaller section of the walkable area. The goal of the lights going out in the hallway of the simulation is to disorient the user enough to where walking back into the "room" section of the physical walkable area will feel like the new, second room.

Development Timeline and Task Allocation

Milestone 1: Establish a project, and complete digital environment design.

- Establish a Unity project and Git repository.
- Create rooms (through modeling or finding assets).
  - Create both rooms and a connecting hallway.
  - Create or find assets such as doors, windows, floors, and gate-control panels.
  - Add signifiers.
    - Indicate the doors are openable.
    - Highlight interactable objects in the space.
- Add lights to the scene.
  - Add directional lighting.
  - Add lighting inside rooms and hallway.
  - Add emergency/fire lights.
- Implement basic lighthouse interaction.
  - Build first lighthouse device.
  - Implement 3D tracking (basic version).

James and Jessica will focus on bringing together a digital environment in the Unity editor while Michael and Alex determine what the creation and integration of the lighthouse sensors entails.

Milestone 2: Add visual effects to enhance presence, establish interactions and Lighthouse for location and orientation sensing, and finalize the moral dilemma.

- Create visual effects for signs of destruction (in order to increase the presence of the experience).
  - Cause objects to "crash" and make noise. Sometimes they will be used to block off the user from returning to a certain area, such as backtracking through the hallway.

- Implement flickering lights without causing simulator sickness.
    - Add some ambient, smoky haze.
    - Start fires in non-interactable locations, also implementing glowing effects.
- Create Intelligence for destruction
    - Create code to handle the order and timing of destructive cues designed
- Implement lighthouse interaction.
    - Build second lighthouse.
    - Implement 3D tracking (advanced).
    - Implement rotation/direction.
- Implement virtual control panel.
    - Implement non-interactable parts.
    - Implement interactive parts.
- Finalize the moral dilemma.
    - Determine the characters involved.
    - Clarify each possible path, including the tasks involved and their consequences.
    - Implement basic character animations.

James and Jessica will focus on the visual effects, and Alex and Michael will continue improving the interaction mechanisms. All four will determine the exact moral dilemma of the simulation and start implementing components specific to it, such as characters.

Milestone 3: Continue increasing interactions, and add spacial audio.

- Integrate lighthouse sensors for interaction with gate-control panels.
- Incorporate breathing sounds to act as the user's own breathing.
- Plan and record character dialog.
- Create intelligence for mission success/failure

James will focus on improving the presence that the user experiences through cues such as breathing. After discussing dialog ideas with the entire group, Jessica will incorporate voices for the characters. Michael and Alex will finalize the physical interactions of the experience.

Resources

[1] Mel Slater, Maria V. Sanchez-Vives. 2016. Enhancing Our Lives with Immersive Virtual Reality. DOI: https://doi.org/10.3389/frobt.2016.00074

[2] J.J. Thomson. 1976. Killing, letting die, and the trolley problem. *Monist.* 59, 204–217. doi:10.5840/monist197659224

[3] Carlos David Navarrete, Melissa Marie Mcdonald, Michael L. Mott, Benjamin Asher. 2011. Virtual Morality: Emotion and Action in a Simulated Three-Dimensional "Trolley Problem." DOI: 10.1037/a0025561

[4] Jaehee Cho, Yeongmin Won, Atit Kothari, Stephanie Fawaz, Zixu Ding, and Xu Cheng. 2016. INJUSTICE: Interactive Live Action Virtual Reality Experience. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (CHI PLAY Companion '16). ACM, New York, NY, USA, 33-37. DOI: https://doi.org.libproxy.clemson.edu/10.1145/2968120.2968121

[5] Lighthouse Sensor Git Repository: https://github.com/ashtuchkin/vive-diy-position-sensor

Appendix E Comparing the RGB Token and the Microsoft Surface Dial

The Microsoft Surface Dial [45] was briefly described in section 3.3.0.4. Here, I compare the Microsoft Surface Dial and some of my own choices while developing the RGB Token.

This comparison will not be based on build quality, aesthetics, cost, or production practicality, as the device is a research prototype, and Microsoft Dials are mass-produced consumer devices. Instead, I will focus on the connection technology, user input, feedback, and sensing of position and orientation strategies.

Several properties were shared by the devices. For connection, the RGB Token employs a Bluetooth module, and the Microsoft Dial employs a Bluetooth LE [31]. Although no difference in functionality can be perceived between these two standards, Bluetooth LE requires less energy, providing longer battery life for the Microsoft Dials. At the time (mid-2016), cost and availability were two main factors that motivated us to choose the less energy efficient Bluetooth version. In terms of input, both devices provide the user with buttons. The RGB Token has a capacitive button at the top, while the Microsoft Dial allows the user to press its body, which functions as a button. Both devices allow interaction on- and off-screen. On-screen interaction can be achieved with the Microsoft Dial only when paired with a Microsoft Surface Studio machine. In this situation, the position of the token is sensed when on top of the display. When paired to other machines, the position is not detected. We proposed a workaround for this limitation with one of the hybrid tokens developed by us. The RGB Token can be used on- and off-screen on any machine. However, we recognize several limitations with our color-sensing approach (e.g. variation in light or color reproduction by different displays can require the RGB Token color sensor to be re-calibrated). Orientation is sensed mechanically, with a rotary sensor in the Microsoft Surface Dial, while magnetically, with a compass module in the RGB Token. Current state of magnetometer technology mean that the precision of these sensors is good, however drift, which is the change in absolute error over time, may cause readings to diverge, so orientation sensing is not precise with the RGB token. The mechanical solution adopted by Microsoft also has drawbacks. It is a more complex system, and may degrade over time, as mechanical pieces wear-off.

In terms of feedback, the strategies of each device also diverge. The RGB Token adopts a visual and audio feedback. The Microsoft Dial provides tactile feedback in the form of micro-vibrations of the dial, as it is turned. While the visual and audio capabilities of the RGB Token can be controlled by the developer, the tactile feedback of the Microsoft Dial cannot be programmed by a developer to express feedback beyond what was intended by Microsoft. Figure 2 summarizes the comparison between both artifacts.

	RGB Token	Microsoft Surface Dial
Connection	Bluetooth	Bluetooth LE
Input	Capacitive button	Mechanical button (body)
Interaction	On- and off-screen	On- and off-screen
Position	RGB color sensor	Proprietary (possibly n-trig)
Orientation	Magnetometer	Mechanical rotary sensor
Visual Feedback	Yes	No
Audio Feedback	Yes	No
Tactile Feedback	No	Yes

Figure 2: **Comparison between the RGB Token and the Microsoft Surface Dial.** *Connection, input strategy, and interaction are very similar between devices. User feedback, however, diverges. The RGB Token applies visual and audio feedback, while the Microsoft Dial employs tactile feedback.*

Appendix F Fullborn Tangibles: Framework, Heuristics and Deployments

In recent decades, 3D printing, laser cutting, and other personal fabrication technologies have established themselves both as major enabling technologies for fabricating research-related interactive systems, and as technology touchstones in popular culture. These fabrication technologies are increasingly supporting the creation of highly functional, robust, safe, and aesthetically refined artifacts, even when produced as research by individuals, and small teams. Such artifacts are increasingly taken beyond the lab environment, to long-term deployments (in the home or elsewhere), live public presentations, live conference demos, among others.

Figure 3: **Examples of fullborn tangibles. Each object was engaged by hundreds of users out of the lab environment.** *(top row) Capacitive sensed dials were part of poster sessions at several conferences. (middle) EtherInstruments were presented at a Maker Faire, and a live music presentation. (bottom) VintagePong controllers, and the VRFishing Rod were part of a conference workshop, and a conference demo session.*

Figure 4: **Examples of fullborns.** *a) COMB modular tangible interface for electronic musical pre-education; b)Fab FM – radios created by users during workshops; c) FireFlies – lighted-objects that display information in classrooms; d) Drift Table – electronic coffee table that displays slowly moving photography. (images from prior ACM publications [229, 193, 87, 132]; permissions remain to be negotiated with source authors)*

There are many challenges related to such "in the wild" environments [146]. Since they are intrinsically less controlled than the lab, it is hard to predict the population who will engage the devices, their behavior while engaging them, and to recover when systems, and devices fail. Creating devices that will successfully operate in such environments requires understanding a number of challenges related to design, fabrication, and deployment.

These types of encounters benefit from a type of research artifact beyond the typical framing of prototypes, in which the artifact is not just a placeholder for future outcomes [176], or the embodiment for a theoretical concept [282], but also a 'final' object in its own right, designed to support out-of-the-lab engagements.

In this appendix, I develop the concept of *fullborns*. I regard fullborns as cyberphysical artifacts that support research encounters between humans and computationally-mediated systems, out of the controlled environments of research labs, with artifacts which are functional, robust, safe, visually refined, and can function and perform similarly to "final products."

Efforts by others, involving devices of this kind include [87, 88, 133, 143, 155, 193, 229, 291]. I later position these, and other examples within the design space shared by *fullborns*, *research prototypes*, and *research products* [206].

Another goal of this appendix is to articulate fullborns through analysis of several of my own cases, stretching over several years of research practices within the university, and elsewhere; across several cities, states, and two continents, including re-visiting the Entrada Poster platform (section 4.9), the VR Fishing Rod 5.7, and others. These experiences led to articulation of a framework of six dimensions which characterize fullborns; and to the LAVA heuristics, which provide a conceptual tool for designing interaction with fullborns. I establish the notion of fullborns, and identify broad common dimensions that I hope can be further refined by researchers, and practitioners in the HCI community.

I next describe several examples of fullborns by others. Then, I define the design space of fullborns, and position several examples. I present a framework with complimentary dimensions of fullborns, and heuristics to pursue good design. Drawing on these dimensions and heuristics, I describe, and analyze four research cases of my own, that exhibit varying levels of success at fulfilling the properties of fullborns.

F.1 Background of Motivating Examples

F.1.1 Functional Prototypes in Demo Sessions

In 1968, the mouse was revealed to the world, when Engelbart presented what became known as the "Mother of All Demos", at the Fall Joint Computer Conference in San Francisco [123]. In many ways, his presentation became the gold standard for demo sessions.

Half a century after Engelbart's presentation, we find several examples of digitally fabricated, highly-functional artifacts showcased at scientific conference demos. Often, these objects are manipulated by tens, if not hundreds of people during those sessions. One such example is COMB [229]. COMB is a modular tangible interface that supports electronic musical pre-education. An example recording [33] illustrates a robust, responsive, and functional 3D printed device, which carries many characteristics embodied by fullborns.

F.1.2 Functional Prototypes in Workshop Sessions

Fab FM [193] investigated design, customization, and fabrication of FM radios created by users during workshops. Users were shown how to manually customize and build their own radios, mostly based on custom hardware and laser cut bodies. Fab FM illustrates some of the possibilities, and feasibility of digital fabrication of fully-functional consumer electronic products. This is aligned with fullborn's perspective of objects that go beyond the notion of prototypes, and embody many characteristics of 'final' products.

F.1.3 Functional Prototypes in the Classroom

FireFlies [87] uses lighted-objects to display information in classroom environments. A working prototype of FireFlies was deployed in four different classrooms for six weeks. As a measure of its success, even after the study had ended, teachers kept reaching for the devices, and mentioned they missed FireFlies. Other highly functional objects inside primary school classrooms are CawClock, and NoteLet [88]. CawClock is a physical clock designed to provide peripheral time awareness by using sounds, and NoteLet is a wrist worn device which allows teachers to mark moments which they want to remember later, by taking photos.

While these efforts give teachers control over the physical prototypes, [133] presents several prototypes which are manipulated directly by the children. Turntalk, for example, is a wood pentagon-shaped tangible, with 3D printed components and Arduino electonics, that teaches norms for turn taking within a small group. Children insert play-cards into Turntalk to reserve a turn to talk. ClassTalk teaches norms for turn sharing within a classroom by combining and interconnecting multiple Turntalk modules.

These examples demonstrate the potential of digital fabrication to produce highly functional prototypes that become part of teachers', and students' everyday routines, in an environment in which robustness, and safety are critical requirements.

F.1.4 Functional Prototypes in Live Music Performances

The Reactable [155] was described in section 3.2.2. Conceived in 2003, the Reactable was presented for the first time in a public concert in 2005, and reached the 'real world' and the rock stadiums after being hand-picked by Icelandic songstress Björk for her 2007 world tour. The company Reactable Systems was founded in 2009. Its success and exposition to millions of people, even as a 'prototype,' inspired us to investigate the key properties involved in crafting fullborns.

F.1.5 Functional Prototypes In the Home

Physikit [143] represents data via physical ambient artifacts (PhysiCubes) that can be programmed and configured by non-expert users. PhysiCubes are laser-cut from 3 mm semi-translucent acrylic, and visualize data coming from sensors in the house: through light, vibrations, movement, or air flow. Each cube is wifi connected, and moving parts have protection mechanisms. Physikits

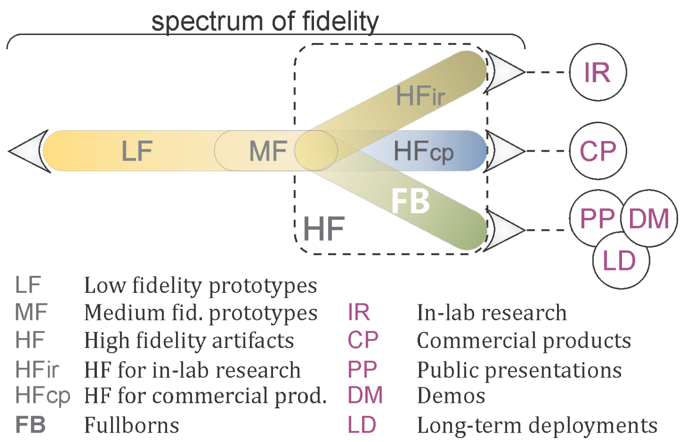


Figure 5: **Alternate representation of the spectrum of fidelity.** *This representation shows fullborns, high fidelity artifacts designed for in-lab engagements, and high fidelity artifacts designed toward commercial products. Each path motivates distinct, but sometimes complimentary, design and fabrication requirements.*

were deployed to the homes of 5 families, for two weeks. Initially, users were instructed on how to deploy the systems in their homes, and received follow up phone calls at pre-scheduled intervals. Researchers visited the homes of the users only during a final interview, after a 10-day deployment. Several aspects of the fullborns concept are present in Physikits. They were *robust*, sustaining use without researchers' support. They also were *safe*; 3 out of the 5 families chosen had young children. Visually, however, there was room for improvement, toward making devices blend more easily with other objects in the home. We later classify Physikits in a class between research prototypes, and fullborns called *quasi-fullborns.*

In another effort involving home deployments, Gaver et al. [132] developed Drift Table, an electronic coffee table that displays slowly moving aerial photography according to the distribution of weight on its surface. Their investigation about how technologies for the home could support ludic activities led them to create a highly-functional, aesthetically refined fullborn. The artifact was successfully deployed to several participants, which hosted the Drift Table in their homes for several weeks.

In the following sections, I first characterize these fullborns broadly within the spectrum of fidelity; then, consider the design space, and properties of fullborns.

F.2 Fullborns and the Spectrum of Fidelity

A range of prototyping methodologies are generally described within a *spectrum of fidelity*, with low-fidelity such as paper sketches at one end, and highly developed, highly interactive artifacts at the other [90]. Although the terms "low-" and "high-fidelity" are often used, the concept of "fidelity" may describe several orthogonal aspects of a prototype. On this subject, McCurdy et. al [190] comments:

> "...it is unclear whether "fidelity" refers primarily to level of functionality, level of visual polish, or level of interactivity (among others)."

Others have argued for broader concepts beyond a single-path continuum to characterize diverse prototyping approaches in use today [190, 129, 268, 144]. Floyd [129] recognizes the need to understand the utility and types of prototypes in practice, pointing out several existing examples. Virzi et al. [268] proposes several orthogonal dimensions, including some of those listed here. Houde and Hill [144] focus on the use of prototypes as a dimension for characterization. Characterizing fullborns simply as "high-fidelity" prototypes does not seem to offer HCI practitioners any particular insights. Inspired by [129, 144] and [268], I next expand on the notion of "low-" vs. "high-fidelity" prototypes by presenting an alternate visual representation of the spectrum of fidelity.

F.2.1 Expanding the Spectrum of Fidelity

One alternate visual representation, based on the spectrum of fidelity, is depicted in Fig. 5. I seek to visually communicate the distinction between prototypes geared towards commercial products, toward in-lab research, and fullborns.

To this end, the representation includes characteristics of Venn diagrams [233], in which each curve defines a collection or family of artifacts. Along the path, three collections are formed: *low-, mid-, and high-fidelity* artifacts. The latter is sub-divided into three collections: high-fidelity devices, adapted for fully realized commercial products; adapted for in-lab research; and adapted for out-of-the-lab encounters, containing fullborns.

Instead of trying to define rigid borders between these three groups, my intention is to help visualize, and communicate shared characteristics between these three broad groups, while exposing the different goals, and intended uses that motivate their distinction. I next describe the design space of fullborns as it relates to the notion of *research prototypes*, and *research products* (Fig.6),

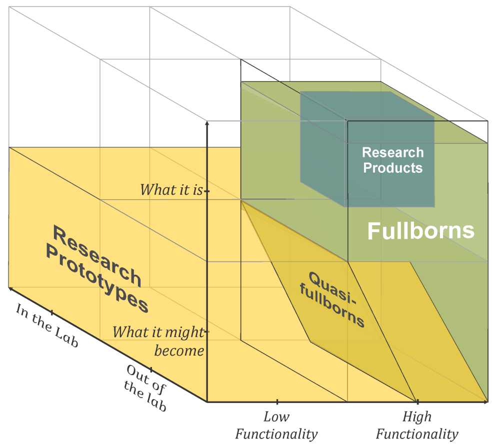


Figure 6: **Design space of fullborns considering research prototypes and research products.** *This representation considers in- and out-of-the-lab engagements, with low and high fidelity devices; Objects which are engaged for what they are (research products, and fullborns), and those which are engaged for what they might become (research prototypes). This representation, similar to subway and other transit maps, is an schematic diagram that supports visualization, without aiming to be proportionally accurate to the number of items that may exist in each section.*

and position examples by others, and myself within this space (Fig.7).

F.3 Design Space

Often, *research prototypes* may be regarded as placeholders for a future outcome [176], the embodiment of the potential of a theoretical concept [282], and are engaged for *what they might become* [206]. Research prototypes may be exposed to in- and out-of-the-lab environments with early stage, or highly functional devices. They occupy most of the base quadrants of the representation (Fig. 6, 7).

In contrast, Odom et al. [206] describe *research products* as highly functional artifacts that people engage with as *they are*, not what *they might become*, which are designed to be lived-with, and experienced out-of-the-lab in an everyday fashion over time (e.g. the home). We position research products partially within the space of fullborns.

Fullborns expand the notion of research products by considering devices which are experienced out-of-the-lab *in general*. Fullborns may include highly-functional objects which are engaged for *what they are* in everyday life scenarios (e.g. in the home, or in the classroom), but also include short-term encounters, and one-off scenarios, such as live music presentations. At the base of the design space, Fullborns include out-of-the-lab encounters in which objects are engaged for *what they*

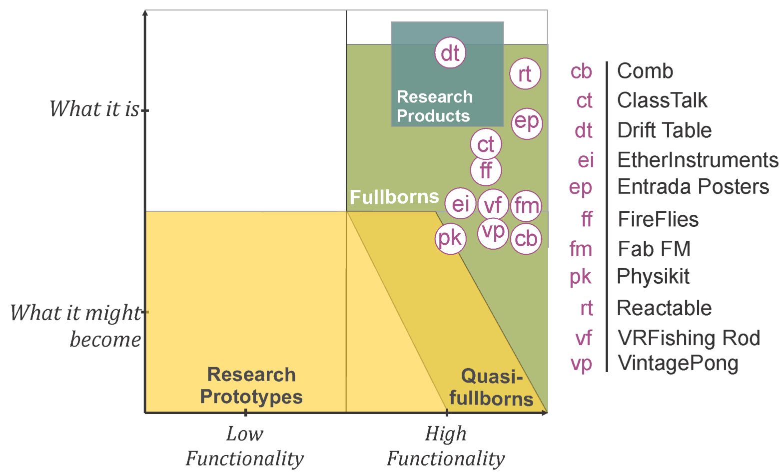


Figure 7: **Design space of fullborns, for artifacts designed for out-of-the-lab engagements.** *Research products are represented as a subset of fullborns. Research prototypes which embody some but not all characteristics of fullborns occupy the area of quasi-fullborns.*

might become (e.g. conference demos and workshops). In the intersection of research prototypes and fullborns there is transitional area with artifacts that fulfill some but not all of the dimensions of fullborns, which I call *quasi-fullborns.* In the next section, I define six dimensions which characterize fullborns – *visual refinement, breadth and depth of functionality, robustness, safety, and ease of deployment* – which help with this distinction.

I have populated the design space with some examples by myself, and others (Fig.7). I next comment on some of the examples and the position they occupy in the design space.

F.3.1 Populating the Design Space

Reactable[155] is positioned at the top right of the space given its high functionality, and exposure to thousands of people in live presentations. Drift Tables represent the group of research products within fullborns. Fab FM [193] is positioned in a region between objects engaged for what they are, and what they might become. Although the objects are highly functional, and capable of blending with (e.g.) the home environment, the nature of workshops is to teach a technique, or technology, which may later be applied when building future devices, hence the positioning in the space. We positioned Physikits [143] to illustrate the notion of quasi-fullborns. The artifacts of Physikits were mainly built from colorful acrylic. Different choices of materials and finish would allow these objects to better blend with the background, helping them to become *true* fullborns.

To further describe fullborns, I defined a characterization method based on a set of dimensions. These dimensions emerged from the analysis, for the past three years, of on-going design, and deployment of computationally mediated tangible systems by the tangible visualization group.

F.4 The Fullborn Six Dimension Framework

I identified six dimensions along which computationally-mediated physical prototypes can be characterized. Like [190], each dimension has a "low-fidelity" and a "high-fidelity" equivalent, but importantly they can be manipulated independently. It became clear, however, that each dimension must be fulfilled, and be present simultaneously to realize the full potential of fullborns. I next describe each dimension:

- **Visual Refinement:** Like [190], this item defines how refined the physical artifacts are in respect to visual finish, and form. This dimension supports legibility, and helps create aspirational, and veritable objects (important aspects of the LAVA heuristic described in the following section). On the low end, we have early-stage prototypes such as wireframe prototypes [199], or prototypes based on LEGO blocks [200]. The high end includes fully formed devices such as [87, 132, 141, 193]. Although a high level of aesthetic refinement may not always be desirable, eliciting more commentary on visual attributes than other aspects, it is often desirable in the later stages of development [190], which is the case for fullborns.

- **Breadth of Functionality:** *How broadly is the functionality represented within the prototype?*[190] The dimension of breadth of functionality emphasizes how actionable artifacts are. Broad functionality in physical prototypes may give users a better understanding of their range of capabilities [232], and offer users the opportunity to experience, and challenge the devices in their entirety [190].

- **Depth of Functionality:** *What is the level of detail of any given feature?* [190] Considering the radios of [193], and [141], the features of those radios are fully functional, granting them high marks in depth of functionality. However, if they were able to tune to a very limited number of radio stations (e.g. one or two), the feature (of tuning to stations) would be present, indicating *breadth of functionality*, but in a restricted way, reducing its *depth of functionality.*

- **Robustness:** *Is the system robust enough to sustain continuous use, by multiple people?* Early-stage prototypes, or those designed for in-lab engagements, are usually expected to perform for relatively short periods of time, and under close supervision. Fullborns may be expected to perform for hours, during several weeks (e.g. at home, or inside classrooms), or in one-off events, such as live presentations. These require consideration for higher levels of robustness to avoid the costs of recovering a failing system that has been deployed out of the lab.

- **Safety:** *Were user safety considerations taken into account?* While rough edges, and even exposed electronics may be present in early-stage physical prototypes designed for in-lab use, this is not always desired in other environments. Physical prototypes designed (e.g.) for the home, or classrooms, especially those in which children are the primary users such as [133], require careful consideration of safety aspects. Sharp edges, exposed moving parts, small parts that may get loose from the prototype and ingested by children, and even the nature of materials that may get in contact with a person's skin are some of the aspects to be considered in relation to safety.

- **Ease of Deployment:** *How complex is the deployment of the devices?* The paper prototypes of [291] required recipients to partially assemble the tangibles, ideally without contacting researchers. This demanded special attention in creating assembly instructions that were clear and concise. Classroom deployments [87, 133] may require both teachers, and possibly students to be trained during deployment. Providing easy setup (e.g. for networking configuration) must also be observed to successfully deploy devices beyond the lab.

F.5 Efforts Toward Fullborns

In this section, I utilize the dimensions, and heuristics outlined to analyze four artifacts deployed in distinct environments. These include re-visiting the *Entrada poster platform, and exploring the EtherInstruments, VrFishing rod and VintagePong controller*. I selected these cases based on my extensive knowledge of their making, and deployments. In my retrospective articulation, not all six dimensions are consistently met by all cases, however, I see these as opportunities for reflection.

F.6 Fullborns in Poster Sessions: the Entrada Poster Platform

In section 4.9, I described the Entrada Poster Platform in the context of interfaces which combine hard-, soft-tangibles, and multi-touch interaction. Here, I revisit that project, with a focus

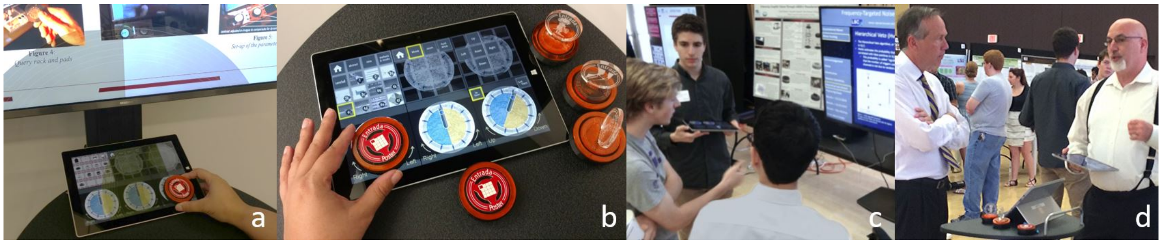


Figure 8: **Computationally-mediated poster platform Entrada.** a) Entrada interface with one or more large vertical screens, and tablets to control interaction. Picture shows detailed of visual feedback as the dial is rotated. b) Detail of the Entrada tablet interface. c and d) Students presenting at the 2017 NSF REU program with the Entrada platform.

on characteristics of the system, its tangibles, and deployment, which embody, and inform the development of the fullborn framework.

As described in section 4.9, in an early effort engaging artifacts in an out-of-the-lab environment, I implemented a computationally-mediated platform for scientific posters. I leveraged on the existence of several communities of content generators from various areas of research, to create content for the *Entrada Poster Platform* [113] (Fig.4).

F.6.1 Scenario and Interaction

Academic conferences are unique opportunities to expose and evaluate our systems beyond the lab environment. In academic conferences, presenters typically stand near their posters for a specified period of time, and present the content to interested groups of visitors, multiple times. During the remaining time, posters are mostly unattended, and users can interact directly with them independently.

Our platform replaces paper posters with screen-based computationally-mediated systems. A full-size poster can be displayed by a vertical screen (in our case, 55-60" diagonal and 3840 X 2160/4k pixels resolution). Microsoft Surface 3 tablets control all aspects of the posters (e.g. selecting content, zooming, manipulating 3D models) with an interface that allows interaction by touch, and by rotational tangibles.

In June and July of 2016, Louisiana State University (LSU) held the 7^{th} NSF REU (Research Experience for Undergraduates) program [27]. Among 12 volunteers, six undergraduate students were selected to participate in ten workshop sessions designed to help them create digital and physical artifacts for the platform, and provide us with feedback. We observed poster creators during 10 weeks, as they created and presented the posters to hundreds of viewers during the NSF REU poster session. Poster creators responded to Likert-scale questionnaires regarding the Entrada platform and their presentations. During the final presentation, hundreds of people viewed, and interacted with the posters, and the tangible interfaces developed for them.

During this experience, the dimensions of visual refinement, breadth and depth of functionality, robustness, and safety appeared both in terms of the digital, and physical artifacts – although at the time not articulated in those terms yet.

F.6.2 Build and Challenges

I will discuss the challenges I faced in light of the six dimensions of the fullborn framework. In terms of *visual refinement*, both the digital posters and the rotational tangibles achieved enough quality to be considered successful, although there is room for improvement. 3D printed tangibles were not as smooth as I would have liked them to be. Interactive posters were fully functional. In terms of *breadth of functionality*, users had the option to exhibit several types of content, from static images, to videos, 3D models, sound files, etc. In terms of *depth of functionality*, users could manipulate and exhibit content in several ways. Users had full access to zooming, rotating and navigating most elements in each poster, among other actions. Every action within the poster could be triggered by using the tangibles, or by hand, with the multi-touch screens of tablets.

In terms of *robustness*, posters were presented during a 3-hour session, and later in multiple other venues. I was prepared for some forms of failure. E.g. I had spare tablets, in case some of them failed, or ran out of power. Hundreds of people interacted with the posters, sometimes accompanied by a presenter, sometimes by themselves. I actively worked on strategies to ensure the posters were *safe*. Display stands were specially robust, and were not easy to tip. I created custom tangibles so that they were not too heavy, and had no moving, or detachable parts. Looking back at the design, laser-cut acrylic on the top of the tangibles had sharp edges. I would most likely review that design to avoid this characteristic.

I cannot claim high marks for *ease of deployment*. Each poster system weighed several pounds, and deployment was a laborious task. With the poster session happening several buildings across campus, and with a limited time to setup before the start of the session, I began to perceive the need to account for deployment concerns. I obtained wheeled carts and loaded them with all the equipment for each poster, created checklists for the components, and brought my own wireless

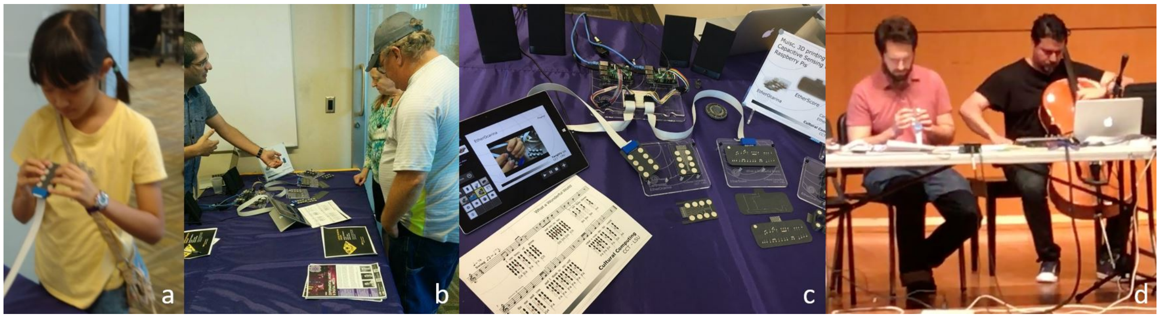


Figure 9: **EtherInstruments.** *a) Girl playing an EtherOcarina at a Maker Faire in October 2016. b) Older couple learning about the EtherInstruments. c) Detail of the EtherInstruments presented at the Maker Faire. d) Composition by a graduate student for the EtherOcarina, and a cello being presented to a live audience in September 2017 at the LSU Music Hall.*

router to the venue.

As a result of these efforts, three of the posters received *best poster* awards. After the end of the REU program, some of the students presented their posters with my platform in several other venues, within the boundaries of the university, and elsewhere. One of them was later invited, and presented at the national level of REU, in the state of Virginia. As an extension of this work, another set of posters were developed. This time, the creation of posters was part of the Tangible Embedded Interaction (TEI) undergraduate course offered at Clemson University (CU) in the fall of 2017, with presentations happening within the class environment. Seven posters were created by students. Over two dozen posters have been created with the platform to date.

F.7 Fullborns in Live Music Presentations: EtherInstruments

In mid 2016, as part of my research efforts developing systems involving highly functional, computationally-mediated physical prototypes, our research group purchased a Voxel8 3D printer (`voxel8.squarespace.com`). The Voxel8 leverages an advanced technology [77], which enables integrating 3D printed thermoplastic with an ability to 3D-print wires using conductive ink. The capabilities of the printer, and interdisciplinary nature of our team, led us to pursue the fabrication of a class of musical instruments called *EtherInstruments*.

EtherInstruments are fullborns that can be digitally fabricated on-demand, as if they were being created "out of the ether." Fig. 10 and Fig. 11 depict two instruments created using this technology, the *EtherOcarinas* and *EtherScores*.

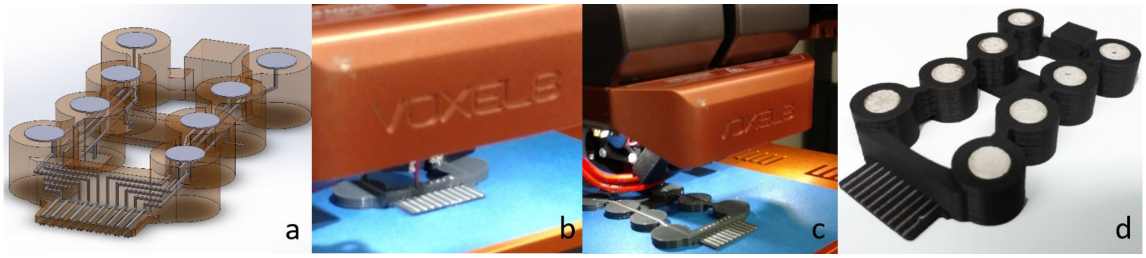


Figure 10: **EtherOcarina design and fabrication.** *a) 3D model of the EtherOcarina. b and c) EtherOcarina with conductive wires being 3D printed by the Voxel8 machine. d) 3D printed EtherOcarina.*

- *EtherOcarina:* The ocarina is a member of the flute family that appeared about 12000 years ago. The *EtherOcarina* is a capacitive music interface, comprised of PLA thermoplastic and conductive ink, that can be directly 3D-printed and connected to a Raspberry Pi to produce music. The EtherOcarina has two octaves of a chromatic scale, and was designed for music education for children, performing diatonic music, and performing electronic music.

- *EtherScore:* Prior to digital music representations becoming popular, musical scores have been stored in alternative formats (e.g. paper, piano rolls, and music box discs) [96]. An *EtherScore* is a capacitive-sensitive musical score that can be printed on-demand and used for memorizing/learning the notes of a musical score, lessons in sight singing, and performing electronic music.

On Sept. 19, 2017, a piece composed specifically for the EtherOcarina was performed in front of a live audience of over a hundred people at the LSU School of Music (`lsu.edu/cmda`). The piece involved the EtherOcarina and a cello (Fig.9d). A video of the presentation can be found at `youtu.be/ZGEVxao7g6g`.

Both instruments were displayed in an interactive setting at a local Maker Faire on Oct. 8, 2016. Over the course of the day, hundreds of people of diverse ages were able to interact with the instruments, playing sections of songs such as "What a Wonderful World" by Louis Armstrong. Most visitors found the interfaces fun, engaging, and interesting tools for learning music. Some visitors wished that the instruments could be connected to a video-game, to add more interactivity.

Although not fully articulated at the time, both objects embodied the six dimensions of the fullborn framework, and the LAVA heuristics. Visually, several musicians were consulted to guide our designs, to create objects that were not just aesthetically refined, but also legible (to musicians), actionable (capable of playing real compositions), and aspirational. Both in terms of *breadth and*

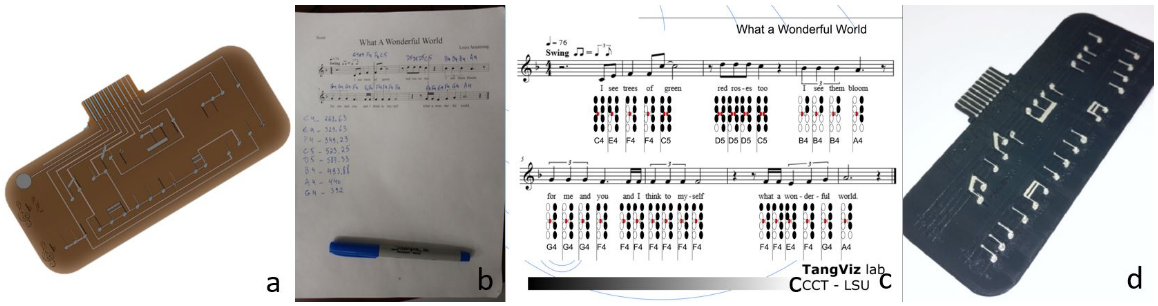


Figure 11: **EtherScore.** *a) 3D model with capacitive wires exposed. b and c) Music Tablature for the song "What a Wonderful World". d) 3D printed EtherScore.*

depth of functionality, the objects achieved high marks. As an example, both musical instruments have the ability to sense not just button press events, but also the area of a button that is being pressed, affecting the output. Both objects proved to be *robust*, and sustained manipulation in public settings by hundreds of people, including children. A lot of effort was put into designing and building 3D printed ribbon cable connectors, to firmly connect our instruments to Raspberry Pis.

In the early stages of development, I learned that the conductive ink was not *safe* for manipulation, due to its corrosive nature. I found a workaround by coating the buttons with a layer of transparent nail polish, hence avoiding direct contact between the conductive ink and the skin.

After the experiences with the Entrada Platform, and EtherInstruments, I began the first articulations toward the fullborn concept, and its dimensions. Having presented several of our systems to hundreds of people within the boundaries of our university, our city, and across states, I next describe presenting fullborn systems in two distinct countries in the European continent. The venues were a conference workshop session at the 2018 IEEE VR conference (`ieeevr.org/2018`), in Reutlingen, Germany, and a demo session at the 2018 TEI conference (`tei.acm.org/2018`), in Stockholm, Sweden.

F.8 Fullborns in a Conference Tutorial Session: the VRFishing Rod

In March 2018, Ayush Bhargava, a fellow Ph.D. student at Clemson, and I presented a workshop session at the 2018 IEEE VR conference. Building upon the experiences described in chapter 5, the tutorial explored the topics of tracking, augmenting, and combining fabricated, and commercially available commodity devices within virtual reality environments. In this context, I designed and built the *VRFishing Rod*, the *VintagePong Controller*, among others (Fig. 12, 14).

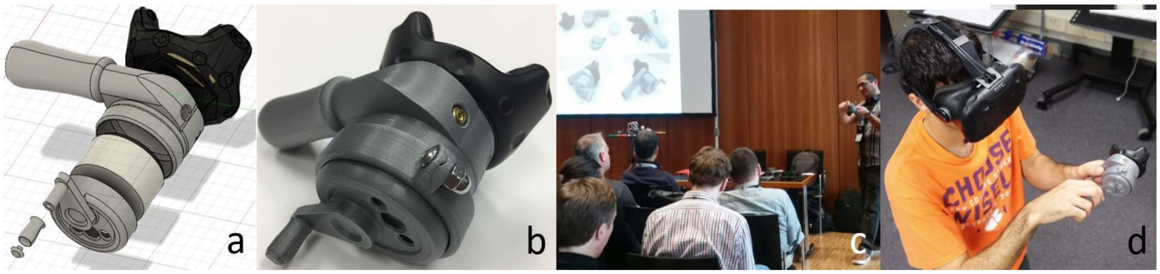


Figure 12: **VRFishing Rod.** *a) 3D model of the VRFishing Rod. b) Refined 3D printed version, in which sharp edges were removed, and rotational dial was secured in place. c) Tutorial session at a conference presenting the artifact. d) User experiencing the virtual reality simulation with the VRFishing rod.*

The 3-hour workshop was attended by aprox. 50 participants. They were presented with theory, hands-on activities and demos, giving them a chance to try out several devices.

F.8.1 VRFishing Rod

The final version of the VRFishing Rod was the product of several iterations. Next, I describe the simulation developed, the interaction, implementation details, challenges I faced, and elements that support the characterization of this object as a fullborn.

F.8.2 Scenario and Interaction

Once the user dawned the HTC Vive head-mounted display (HMD) [66], he/she was presented with an immersive virtual environment that featured a lake, and a fishing deck. The user started off standing at the edge of the fishing deck, and was handed the custom built VRFishing Rod, which has an HTC Vive tracker attached to one side. He/she was then instructed on casting the bait by swinging the physical object, and reeling a fish in, by rotating the reel's lever. Since the simulation was created for the tutorial, no scores, or competitive goals were put in place. The simulation was developed using the Unity 3d game engine.

F.8.3 build and challenges

To achieve a high level of *visual refinement*, I first used 3D modeling tools suitable for fast prototyping (e.g. SketchUp (`sketchup.com`)) to understand basic proportions. Later, I switched to more advanced 3D modeling tools (e.g. Fusion 360 (`autodesk.com/fusion360`)) to refine the design. Final objects were printed at high resolution (0.05 mm layer thickness - 3-hour printing

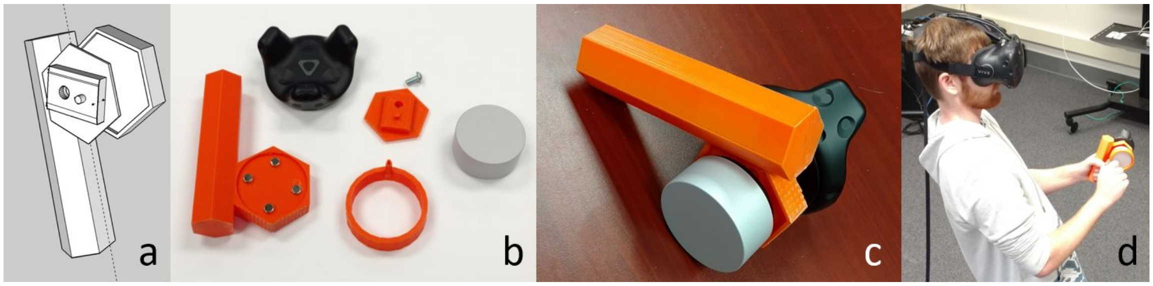


Figure 13: **Early prototype of the VRFishing Rod.** *a) Initial 3D model of the VRFishing Rod. A number of sharp edges were present. b) 3D printed parts. Both the Dial and the VR tracker were attached to the body of the fishing rod by magnets. This strategy was later replaced by crews. c) 3D printed VR Fishing Rod. d) User experiencing a virtual reality simulation with the VRFishing rod.*

time). At this resolution, 3D printed objects can be smooth to the touch, and create attractive objects, without the need for additional treatments (e.g. sanding, or painting). However, the design I created did not allow the object to lay flat on the surface of the 3D printer bed, meaning that several sections of the object required supports during printing. Supports reduce the quality of the face they touch, so I had to carefully choose the positioning of the object during printing to obtain the optimal final product finish. I employed a Flashforge Creator Pro 3D printer [37] in this build. This printer is capable of a building volume of 8.9L X 5.8W X 5.9H in. This restricted the final size of the object, which led to the creation of a slightly smaller handle than I had first envisioned.

To achieve high levels of *breadth and depth of functionality*, I embedded a Microsoft Surface Dial [20] inside the 3d printed body. It captures the user's rotational gestures, and button-press actions. The Dial also provides haptic-feedback, which adds to the experience of fishing in VR.

I aimed at creating a *robust and safe* object. My main challenge was the physical integrity of the object during usage. My initial prototype employed magnets (Fig.13) to hold the tracker, and the Dial connected to the central structure of the object in place. While this approach seemed satisfactory during development time, in the hands of the researchers, pilot tests revealed that users tend to apply much more force when casting the bait than originally anticipated, especially because the virtual reality simulation made the experience more immersive. Since magnets were not sufficiently strong, the tracker, and the Dial would often dangerously fly away. I started to search for designs that would maintain the integrity of the object during use. After several iterations, I created a design (Fig.12) that held its structural integrity. The magnets that held the tracker in place were substituted by a metal screw connected to the body of the object. The Dial presented a

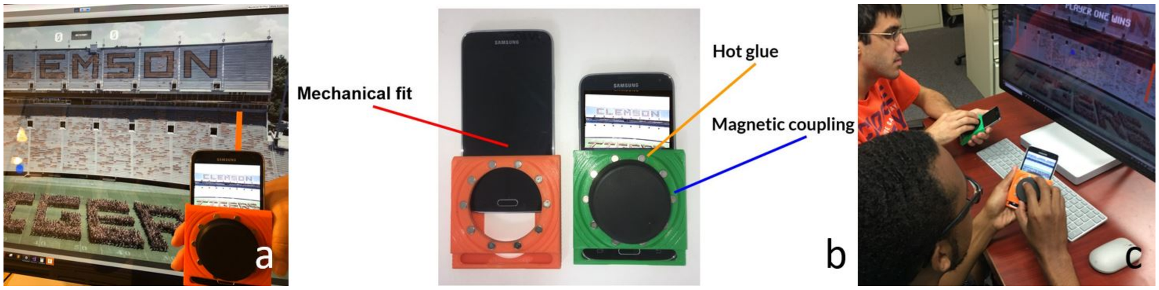


Figure 14: **The VintagePong controller was modeled after the original Atari paddles.** *a) I re-purposed a ~5 year old phones by fabricating functional elements made of conductive 3D printed thermoplastic that interact with the multi-touch screen of the phone. b) Detail of the contruction of the controllers. c) Users playing with the pong game.*

bigger challenge to secure in place, since I had to keep it in place while allowing it to rotate. After careful consideration, I devised a locking ring, that kept the dial from falling, while allowing free rotation.

In terms of *deployment*, it became clear that the system lacked refinement. While deploying the device was trivial, current virtual reality tools are in most part cumbersome to travel with, and to setup. Drawing lessons from presenting digital posters in several venues, I systematically planned the *deployment* of our artifacts overseas. Considering travel weight and size limitations, providing our own wireless network, and considering power plug standard differences across countries, proved to be valuable considerations to achieve a successful deployment. One member of our research group jokingly suggested that the complexity was similar to *putting on a rock concert*.

F.8.4 VintagePong Controller

The *VintagePong Controller* was inspired by vintage paddle controllers [49]. I augmented two Samsung Galaxy S5 smart phones with 3D printed sleeves containing the paddles for the controllers. To create an *aspirational* artifact, I chose 'old' smart phones as a way to *give new life* to objects that would otherwise be discarded. The controllers were paired with a customized version of the classic Pong game, originally created by Atari in 1972 [50]. Our game was developed using the Unity 3d game engine.

Sharp edges were avoided for *safety*, and *robustness* was achieved by careful fit between the phones and 3D printed elements. For *functionality*, I employed *conductive PLA*, and conductive rubber pads in contact with the phones' multi-touch displays to capture the rotation of the paddles.

Screens were partially exposed, and displayed scores, and UI buttons.

The devices were *actionable*. For about 15 min. prior to the beginning of the workshop session, and later, at the end of the session, attendants played the Pong game, taking turns in a round-robin fashion. They were also *legible and veritable*. Most of the participants enjoyed playing the game with the controllers, and were satisfied with their performances without any previous instruction or comment from ourselves. Some of the attendants were *disappointed* that they had to stop playing so that the session could start. To us, it was a sign of having built a successful system, and tangible artifacts.

Later, the controllers were also presented at the 2018 TEI conference (`tei.acm.org/2018`) at a demo session. There, the focus was the combination of tangible, and multi-touch interfaces. Once again, the Pong controllers were exposed to hundreds of people. In particular, I observed the excitement of a father of two boys showing his sons how he used to play that game in his infancy. He expressed his desire for experiencing more variation in existing physical controllers. I believe this meets the *aspirational* quality in the LAVA heuristics for this pair of devices.

Back in our lab, both devices have been exposed to groups of 10 to 20 visitors approximately periodically, and have been taken to other venues such as the MakerDay events at Clemson (`www.cumake.it/makerday`), continuing to add to the number of users experiencing these fullborns every month.

F.9 Discussion

F.9.1 Prototyping Frameworks

Engelbart's demonstration of the mouse to the world in 1968 became known as the "Mother of All Demos" [123]. For that presentation, in powerful partnership with transformative system and hardware innovations, he did not use the first fully-functional prototype of the mouse, which was handcrafted in wood in 1963. Instead, he used the more visually refined first production-run mouse based on his original design.

While I do not know the reasons why Engelbart chose to use the production-run instead of the fully-functional prototype during the demo, I suspect some of the reasons may be similar to what they might be today. The fullborn framework and heuristics aim at balancing the needs of look and feel, with form and function. If artifacts created are visually refined, but lack functionality, users may feel disappointed and easily loose interest. On the other hand, highly functional devices that are not visually refined may fail to promote pleasurable experiences, not fulfilling the user's expectations. Fifty years after the "Mother of All Demos", whether presenting at demos, or similar venues, many users desire devices that carry a high level of visual refinement, breadth and depth of functionality, robustness, safety, and ease of deployment.

While methodologies engaging early stage software and physical prototypes [90], and towards commercial products [186, 168] have been explored, as noted by Engelberg and Seffah [124], there is relatively little detailed elaboration in the literature of structured methodologies for late-stage prototyping of physical artifacts geared towards research-related activities. As explained by Isensee and Rudd, and still applicable today, *" ... the optimum methods of prototyping have not yet been agreed on"* [148]. This served as motivation to begin exploring frameworks to assist the creation of fullborns.

F.9.2 Validity and Benefits

In controlled experimental studies (e.g. [268]), it was found that "low-fidelity" prototypes are as effective as high-fidelity prototypes for validation with users. In other words, early-stage prototypes capture many usability issues that could be communicated in a late-stage prototype. While dated, these results support that both are valid approaches. So *when* to create high-fidelity prototypes?

In many cases, it would be hard to argue for the added time, cost, and complexity of creating high-fidelity prototypes vs. low-fidelity prototypes for in-lab use. However, if we consider taking prototypes to environments other than the lab, low-fidelity prototypes may not be the best choice. High-fidelity prototypes built for in-lab use may also not be suitable. Therefore, this work contributes by closing a gap in the literature, and defining a framework, and heuristics to develop highly-functional prototypes for out-of-lab engagements.

F.9.3 Final Remarks

My work with tangible user interfaces is closely coupled with the practice in creating highly-functional, computationally-mediated physical prototypes. I have created a number of highly-functional artifacts, many of which were experienced by others, out of the lab environment. This appendix has motivated and investigated the concept of *fullborns*, extending the notion of prototypes directed at out-of-the-lab experiences, encounters, and relationships between humans and interactive artifacts. My goal has been to characterize the dimensions embodied by fullborns, and offer heuristics to successfully design them. The analysis of four cases presented to audiences in different contexts led to the six dimensions of fullborns: *visual refinement, breadth and depth of functionality, robustness, safety and ease of deployment.* I presented how each fullborn dimension emerged in those cases.

My work has provided several insights when building fullborns; 1) combining 3d printing and other digital fabrication technologies (e.g. laser cutting) offer a wide range of materials and fabrication approaches, which best suit the fabrication of fullborns than any single technique. 2) These fabrication approaches may help mold research prototypes into fullborns (or quasi-fullborns) by possibly making them safer, robust, and visually appealing. 3) Fullborn tangibles may increase immersion in VR and, 4) when possible, commercially available devices (e.g. trackers) can be coupled with 3D printed objects to create custom interactive devices with less complexity than building custom hardware.

As the HCI community continues to explore new ways to practice research, and to communicate the production of knowledge, I hope fullborns can be seen as a complementary framing to support the creation of research artifacts that are ready to reinforce these efforts, and more broadly, the need to continuously improve the way we practice, present, and communicate knowledge production in HCI.

Appendix G Informed Consent

Information about Being in a Research Study
Clemson University
Empirical Evaluation of Near Field Size perception of Tangibles in Virtual Reality and Real World Environments

Description of the Study and Your Part in It
Dr. Sabarish Babu and Dr. Andrew Robb are inviting you to take part in a research study. The purpose of this study is to explore users' accuracy in near field size perception.

Your participation may involve:
1. Answering questions about your demographics.
2. Judging the size (diameter) of several cylindrical knobs.
3. Wearing a Virtual Reality/Mixed Reality Headset

It will take you about 1 hour to complete this study. We will record video and audio of your participation for research purposes only.

Risks and Discomforts
There are certain risks or discomforts that you might expect if you take part in this research and it involves wearing Virtual Reality headsets. They include minor eye strain or the experience of "simulator sickness", a form of motion sickness. To minimize this risk, we will follow all known practices to reduce the possibility of experiencing simulator sickness. Other labs that have used VR simulators have suspected that nausea may be more likely in participants who have a history of motion sickness. If you have a history of motion sickness, you may not want to participate in this research study. If you believe that you are susceptible to simulator-related nausea or have a history of epilepsy, we recommend that you not participate in this research.

Possible Benefits
We do not know of any way you would directly benefit from taking part in this study. However, this research may help contribute to the broader questions of size perception and the results may impact how we look at tangible objects withing virtual reality simulations as a whole.

Compensation
You will be rewarded with a $15 gift card/ research experience/ course credit/ extra credit upon completion of this experiment.

Protection of Privacy and Confidentiality
No identifying data will be stored, and any data collected will be kept in locked cabinets or password-protected computers to which only researchers associated with this study have access. Any physical documents associated with this study will be stored in a locked cabinet. The results of this experiment will be summarized across all participants, and no information specifically identifying you will be presented. Your identity will not be revealed in any publication that might result from this study. At no point will audio and video recordings be accessible by

any person that is not a part of the research team and these recordings will be stored securely in password protected folders for the duration of study after which it will be deleted.

We might be required to share the information we collect from you with the Clemson University Office of Research Compliance and the federal Office for Human Research Protections. If this happens, the information will only be used to find out if we ran this study properly and protected your rights in the study.

Choosing to Be in the Study
You may choose to not take part in this study or to stop taking part at any time. You will not be punished in any way if you do not take part or decide to terminate the study. This study will not affect your grade in any way. If you choose to stop taking part in this study, the information you have already provided will be used in a confidential manner.

Contact Information
If you have any questions or concerns about this study or if any problems arise, please contact Alexandre Gomes de Siqueira at Clemson University at gomesde@clemson.edu.
If you have any questions or concerns about your rights in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-0636 or irb@clemson.edu. If you are outside of the Upstate South Carolina area, please use the ORC's toll-free number, 866-297-3071.

Consent
I have read this form and have been allowed to ask any questions I might have. I agree to take part in this study.
Participant's signature: ___________________________________ Date: _______________

A copy of this form will be given to you

Appendix H Research Protocol

Empirical Evaluation of Near Field Size perception of Tangibles in Virtual Reality Protocol

1) Before receiving the participant
   a) Turn on pc if it is not already on.
   b) Login using the local account
   c) Open SteamVR from the taskbar or icon tray.
   d) Make sure SteamVR is running. You should see the SteamVR icon in the system tray icons, right side of the taskbar.
   e) Make sure that the HMD is being tracked (It should look like Figure 1)
      1) If it's frozen, quit and start SteamVR again.

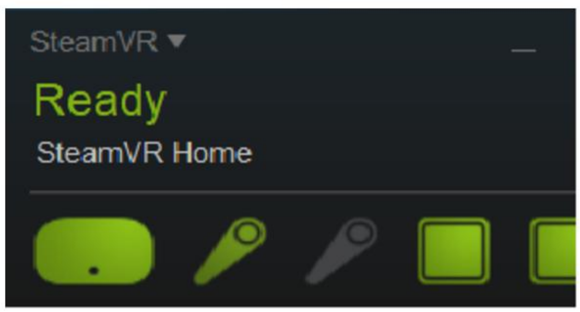


Figure 1

   f) Make sure the vertical multi-touch display is placed in the marked position of the room.
   g) Make sure the dial table is positioned 38 mm from the left edge of the table.
2) Start the Unity program *PerceptionAction-Main2018UI-imported* in the desktop machine
3) Calibrate the scene
   a) Position the control with a white sphere with its tip at the lower left corner of the dial table and press c on the keyboard.
4) Start the reporting Unity program on the multi-touch screen
   a) Turn on the Microsoft Studio machine (lower right corner button)
   b) Hit CTRL+ALT Delete to enter password
   c) Enter the password: imagine
   d) If reporting program is running, close it (Alt+Tab and close from the task bar)
   e) Click on the white icon with a blue hand on the task bar to start the reporting program
   f) Touch the screen and move the finger to check if the program is running

5) Receive the participant, ask him/her to sit on the chair
6) Present the participant with the Informed Consent form
7) Ask participants to sign the Informed Consent form
8) Ask the participant to fill out the Pre Study survey
    a) Open a new browser window
    b) Paste the link:
    https://clemson.ca1.qualtrics.com/jfe/form/SV_7PP5OLV3ZXo3OGp

9) Measure participant's inter-pupillary distance
    a) Open the PD Meter app, follow the app instructions
    b) Calibrate the interpupilary distance on the HMD

10) Choose the trial type
11) Enter the User's Participant ID

12) Ask the participant to move to a position between the dial table and the reporting screen.
13) Ask the participant to seat facing the the reporting screen.
14) Ask the participant to adjust the HMD. Assist if necessary.
15) Click the Report Information button
16) Explain the participant what will happen:
    a) For 3.2. and 3.3 (VR Vision Only)
        i) **There are 3 phases**:
        ii) Phase 1
            (1) Researcher
                (a) No need to set physical dials on the tracking table
                (b) Pay attention to the end of the PRETEST PHASE and the beginning of the CALIBRATION PHASE.
            (2) Participant
                (a) Wears the HMD
                (b) Faces the reporting screen
                (c) Upon receiving the message "turn around to begin next trial":
                (d) Turns around, looks at the knob (no physical knob to touch).
                (e) When satisfied, turns around again, and reports the size
                (f) Follows the on-screen instructions
        iii) Phase 2
            (1) Researcher

(a) Instructs the participant **not** to report during calibration
(b) Sets the correct physical dials, presses the button "start trial"
(c) Signals verbally to participant to begin examining the knob
(d) After the participant turns back to the reporting screen, researcher presses the "End trial" button, and sets the new physical dial.
(e) This is repeated for each calibration trial.

(2) Participant
(a) Wears the HMD
(b) Turns to the reporting screen
(c) Upon receiving the message "turn around to begin next trial":
(d) Turns around, looks and touches the the knob. User is requested to also rotate the knob.
(e) When satisfied, turns around again, and waits for the researcher to verbally signal that a new trial can begin
(f) Follows the on-screen instructions

iv) Phase 3 is the same as phase 1.

b) For 4.2. and 4.3 (VR Haptics Only)

i) **There are 3 phases**:
ii) Phase 1
(1) Researcher
(a) Sets physical dials on the tracking table
(b) Pay attention to the end of the PRETEST PHASE and the beginning of the CALIBRATION PHASE.

(2) Participant
(a) Wears the HMD
(b) Faces the reporting screen
(c) Upon receiving the message "turn around to begin next trial":
(d) Turns around, the knob and rotates it.
(e) When satisfied, turns around again, and reports the size
(f) Follows the on-screen instructions

iii) Phase 2
(1) Researcher
(a) Instructs the participant **not** to report during calibration

(b) Sets the correct physical dials, presses the button “start trial”
(c) Signals verbally to participant to begin examining the knob
(d) After the participant turns back to the reporting screen, researcher presses the “End trial” button, and sets the new physical dial.
(e) This is repeated for each calibration trial.

(2) Participant
(a) Wears the HMD
(b) Turns to the reporting screen
(c) Upon receiving the message “turn around to begin next trial”:
(d) Turns around, looks and touches the the knob. User is requested to also rotate the knob.
(e) When satisfied, turns around again, and waits for the researcher to verbally signal that a new trial can begin
(f) Follow the on-screen instructions

iv) Phase 3 is the same as phase 1.

17) Ask the participant to fill out the Post Study survey
a) Open a new browser window
b) Paste the link:

https://clemson.ca1.qualtrics.com/jfe/form/SV_aaPBe5S62QoORNP

18) Pay participant (10$ Amazon gift card)
a) Enter participant’s info in the Incentive Card Distribution Log
i) https://drive.google.com/drive/folders/1eKlkicYG8zU2M4IMnvzG00oQkCO-cCOD?usp=sharing

b) Participants that complete all three phases will receive a $10 gift cards. Participants will receive $5 gift cards if they discontinue the study anywhere in phases 2 and 3.
Participants will not receive gift cards if they discontinue before phase 2.

Bibliography

[1] Adafruit apds9960 proximity, light, rgb, and gesture sensor id: 3595 - $7.50 : Adafruit industries, unique & fun diy electronics and kits. https://www.adafruit.com/product/3595. (Accessed on 09/04/2018).

[2] Annotate images and videos thinglink. http://www.thinglink.com/. (Accessed on 07/19/2017).

[3] Appmates. http://www.appmatestoys.com/. (Accessed on 07/20/2017).

[4] Conductive pla protoplant, makers of proto-pasta. https://www.proto-pasta.com/pages/conductive-pla. (Accessed on 08/31/2018).

[5] Create easy infographics, reports, presentations — piktochart. https://piktochart.com/. (Accessed on 07/19/2017).

[6] Creator pro 3d printer flashforge 3d printers. http://www.flashforge.com/creator-pro-3d-printer/. (Accessed on 08/31/2018).

[7] Das terminal. https://www.dasterminal.com/. (Accessed on 07/19/2017).

[8] Ecology — definition of ecology by merriam-webster. https://www.merriam-webster.com/dictionary/ecology. (Accessed on 12/07/2018).

[9] Google sites. https://sites.google.com/new?usp=jotspot_si. (Accessed on 07/19/2017).

[10] Griffin powermate - wikipedia. https://en.wikipedia.org/wiki/Griffin_PowerMate. (Accessed on 08/26/2018).

[11] How to use glogster - web / desktop. http://webuse.glogster.com/. (Accessed on 07/19/2017).

[12] Interactive posters - web tools for kids. https://sites.google.com/site/webtoolsbox/interactive-posters. (Accessed on 07/19/2017).

[13] Mattel brings powerhouse brands to the ipad with apptivity play — mattel inc. https://goo.gl/cx6o8K. (Accessed on 07/20/2017).

[14] Multieposter - state-of-the-art eposter solution & services. http://www.multieposter.com/. (Accessed on 07/19/2017).

[15] Reactable mobile - android apps on google play. https://play.google.com/store/apps/details?id=com.reactable&hl=en. (Accessed on 07/20/2017).

[16] Reactable mobile on the app store. https://itunes.apple.com/us/app/reactable-mobile/id381127666?mt=8. (Accessed on 07/20/2017).

[17] Software implementing TUIO. http://www.tuio.org/?software.

[18] Suction cup tape. https://www.inventables.com/technologies/suction-cup-tape. (Accessed on 10/29/2018).

[19] Welcome to python.org. https://www.python.org/. (Accessed on 07/26/2017).

[20] Surface dial interactions - uwp app developer — microsoft docs. https://docs.microsoft.com/en-us/windows/uwp/design/input/windows-wheel-interactions, Oct. 11. (Accessed on 10/11/2018).

[21] Unity. https://unity3d.com/, Oct. 11. (Accessed on 10/11/2018).

[22] 55 inch 4k touchscreen smart tv — guaranteed lowest price on touchscreens — music computing. http://musiccomputing.com/motioncommand-55-10-touch-4k/, Oct. 12. (Accessed on 10/12/2018).

[23] Arduino micro. https://store.arduino.cc/usa/arduino-micro, Oct. 12. (Accessed on 10/12/2018).

[24] Beetle - world smallest arduino leonardo — arduino stuff — robot r us. https://www.robot-r-us.com/arduino-stuff/beetle-world-smallest-arduino-leonardo.html, Oct. 12. (Accessed on 10/12/2018).

[25] Facebook spaces. https://www.facebook.com/spaces, Dec. 2017. (Accessed on 12/01/2017).

[26] Moodle - open-source learning platform — moodle.org. https://moodle.org/, Dec. 2017. (Accessed on 12/01/2017).

[27] Research experiences for undergraduates - wikipedia. https://en.wikipedia.org/wiki/Research_Experiences_for_Undergraduates, Jul. 2017. (Accessed on 07/27/2017).

[28] Watch 3d movies on virtual reality glasses or headset - 3d online films. https://3donlinefilms.com/, Dec. 2017. (Accessed on 12/01/2017).

[29] About the friendly swede. https://thefriendlyswede.com/pages/about-the-friendly-swede, Aug 2018. (Accessed on 08/30/2018).

[30] Accessories — oculus. www.oculus.com/rift/accessories/, Oct. 2018. (Accessed on 10/23/2018).

[31] Bluetooth low energy - wikipedia. https://en.wikipedia.org/wiki/Bluetooth_Low_Energy#History, Sept 2018. (Accessed on 09/04/2018).

[32] Challenge coin - wikipedia. https://en.wikipedia.org/wiki/Challenge_coin, Sept 2018. (Accessed on 09/06/2018).

[33] Comb on vimeo. https://vimeo.com/231299236, Jun 2018. (Accessed on 06/29/2018).

[34] Cyberglove iii cyberglove systems llc. http://www.cyberglovesystems.com/cyberglove-iii/, Oct. 2018. (Accessed on 10/23/2018).

[35] Dell canvas dial totem — dell united states. https://www.dell.com/en-us/shop/dell-canvas-dial-totem/apd/750-aayl/pc-accessories, Aug 2018. (Accessed on 08/26/2018).

[36] Dial box - wikipedia. https://en.wikipedia.org/wiki/Dial_box, Jun 2018. (Accessed on 08/26/2018).

[37] Flashforge usa official site. https://flashforge-usa.com/, March 2018. (Accessed on 03/28/2018).

[38] The internet of things consortium. https://iofthings.org/, Dec. 2018. (Accessed on 12/13/2018).

[39] Isomorphic — definition of isomorphic by merriam-webster. https://www.merriam-webster.com/dictionary/isomorphic, Dec. 2018. (Accessed on 12/07/2018).

[40] Kivy: Cross-platform python framework for nui development. https://kivy.org/#home, Oct. 2018. (Accessed on 10/15/2018).

[41] Letters to a young librarian: You can't get there from here: Wayfinding in an academic library. http://letterstoayounglibrarian.blogspot.com/2013/11/you-cant-get-there-from-here-wayfinding.html, Nov. 2018. (Accessed on 11/13/2018).

[42] Lulzbot taz 6 — lulzbot. https://www.lulzbot.com/store/printers/lulzbot-taz-6, Aug 2018. (Accessed on 08/31/2018).

[43] Manus vr — cutting edge vr technology. https://manus-vr.odoo.com/, Oct. 2018. (Accessed on 10/23/2018).

[44] Mattel brings powerhouse brands to the ipad with apptivity play — mattel inc. https://news.mattel.com/news/mattel-brings-powerhouse-brands-to-the-ipad-with-apptivityTM-play, Aug 2018. (Accessed on 08/27/2018).

[45] Microsoft surface dial. https://www.microsoft.com/en-us/p/surface-dial/925r551sktgn?activetab=pivot:overviewtab, Aug 2018. (Accessed on 08/26/2018).

[46] Microsoft/windows-universal-samples: Api samples for the universal windows platform. https://github.com/Microsoft/Windows-universal-samples, Oct. 2018. (Accessed on 10/11/2018).

[47] Neopixel ring - 16 x ws2812 5050 rgb led - com-12664 - sparkfun electronics. https://www.sparkfun.com/products/12664, Sept 2018. (Accessed on 09/04/2018).

[48] Opp_researchbrief6_surveyofmakerspacespart1_final.pdf. http://makered.org/wp-content/uploads/2015/02/OPP_ResearchBrief6_SurveyofMakerspacesPart1_final.pdf, Jun 2018. (Accessed on 06/26/2018).

[49] Paddle (game controller) - wikipedia. https://en.wikipedia.org/wiki/Paddle_(game_controller), July 2018. (Accessed on 07/21/2018).

[50] Pong - wikipedia. https://en.wikipedia.org/wiki/Pong, July 2018. (Accessed on 07/21/2018).

[51] Radialcontroller - is it possible to uniquely identify and use multiple surface dials? issue #751 microsoft/windows-universal-samples. https://github.com/Microsoft/Windows-universal-samples/issues/751, Nov. 2018. (Accessed on 11/05/2018).

[52] Reactable -music knowledge technology. http://reactable.com/, Aug 2018. (Accessed on 08/26/2018).

[53] Reactable live! http://reactable.com/live/, Oct. 2018. (Accessed on 10/18/2018).

[54] Reactable mobile. http://reactable.com/mobile/, Oct. 2018. (Accessed on 10/18/2018).

[55] Replicator 2x experimental 3d printer. https://store.makerbot.com/printers/replicator2x/, Aug 2018. (Accessed on 08/31/2018).

[56] Rotor, tangible modular music synth app by reactable. http://reactable.com/rotor/, Oct. 2018. (Accessed on 10/18/2018).

[57] Rowmark - lasermax product line. http://www.rowmark.com/laser/LaserMAX/lasermax.asp, Sept 2018. (Accessed on 09/01/2018).

[58] Skylanders video game - official site. https://www.skylanders.com/, Aug 2018. (Accessed on 08/27/2018).

[59] Tony mendez receives presidential challenge coin from barack obama - argothebook.com. http://argothebook.com/news/tony-mendez-receives-presidential-challenge-coin-from-barack-obama, Oct. 2018. (Accessed on 10/09/2018).

[60] Touch, input, and hid - windows 10 hardware dev. https://technet.microsoft.com/en-us/windows/dn614616(v=vs.60), Nov. 2018. (Accessed on 11/05/2018).

[61] Uniosc — uniosc the osc solution for unity3d. http://uniosc.monoflow.org/, Oct. 2018. (Accessed on 10/30/2018).

[62] Unity - scripting api: Touch.radius. https://docs.unity3d.com/ScriptReference/Touch-radius.html, Oct. 2018. (Accessed on 10/11/2018).

[63] Uxlx: User experience lisbon - 3 to 5 june 2015. http://2015.ux-lx.com/videos.html, Dec. 2018. (Accessed on 12/07/2018).

[64] Vive — controller. https://www.vive.com/us/accessory/controller/, Oct. 2018. (Accessed on 10/23/2018).

[65] Vive — vive tracker. https://www.vive.com/us/vive-tracker/, Oct. 2018. (Accessed on 10/23/2018).

[66] Vive virtual reality system. https://www.vive.com/us/product/vive-virtual-reality-system/, March 2018. (Accessed on 03/28/2018).

[67] Wemos d1 mini pro esp8266 wifi development board einstronic enterprise. https://einstronic.com/store/controller/esp8266/wemos/wemos-d1-mini-pro-esp8266-wifi-development-board/, Sept 2018. (Accessed on 09/06/2018).

[68] Hatchbox pla gray-1.75mm,1kg spool,3d filament, +/- 0.03mm hatchbox 3d. https://www.hatchbox3d.com/products/3d-pla-1kg1-75-cg6c, June 2019. (Accessed on 06/26/2019).

[69] How to measure pd — glassifyme. https://www.glassifyme.com/how-to-measure-pd, June 2019. (Accessed on 06/30/2019).

[70] Ideum - exhibit design — touch tables — interactive exhibits. https://ideum.com/, July 2019. (Accessed on 07/04/2019).

[71] The moment of lift. https://www.evoke.org/momentoflift, June 2019. (Accessed on 06/19/2019).

[72] Prusa3d - 3d printers from josef prusa. https://www.prusa3d.com/, June 2019. (Accessed on 06/26/2019).

[73] Results acm dl :blind. https://dl.acm.org/results.cfm?within=recurringEvents.recurringEventID%3DRE271&withindisp=TEI&query=blind&Go.x=0&Go.y=0, July 2019. (Accessed on 07/18/2019).

[74] Sustainable development goals - united nations sustainable development. www.un.org/sustainabledevelopment/sustainable-development-goals, June 2019. (Accessed on 06/19/2019).

[75] What is digital inclusion? — digital inclusion survey 2013. https://digitalinclusion.umd.edu/content/what-digital-inclusion, July 2019. (Accessed on 07/04/2019).

[76] Benjamin P Abbott, Richard Abbott, TD Abbott, MR Abernathy, Fausto Acernese, Kendall Ackley, Carl Adams, Thomas Adams, Paolo Addesso, RX Adhikari, et al. Observation of gravitational waves from a binary black hole merger. *Physical review letters*, 116(6):061102, 2016.

[77] Bok Y Ahn, Eric B Duoss, Michael J Motala, Xiaoying Guo, Sang-Il Park, Yujie Xiong, Jongseung Yoon, Ralph G Nuzzo, John A Rogers, and Jennifer A Lewis. Omnidirectional printing of flexible, stretchable, and spanning silver microelectrodes. *Science*, 323(5921):1590–1593, 2009.

[78] Bliss M Altenhoff, Phillip E Napieralski, Lindsay O Long, Jeffrey W Bertrand, Christopher C Pagano, Sabarish V Babu, and Timothy A Davis. Effects of calibration to visual and haptic feedback on near-field depth perception in an immersive virtual environment. In *Proceedings of the ACM symposium on applied perception*, pages 71–78. ACM, 2012.

[79] David Anderson, James L Frankel, Joe Marks, Aseem Agarwala, Paul Beardsley, Jessica Hodgins, Darren Leigh, Kathy Ryall, Eddie Sullivan, and Jonathan S Yedidia. Tangible interaction+ graphical interpretation: a new approach to 3d modeling. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 393–402. ACM Press/Addison-Wesley Publishing Co., 2000.

[80] Leonardo Angelini, Nadine Couture, Omar Abou Khaled, and Elena Mugellini. Interaction with the internet of tangible things (iott). In *CEUR Workshop Proceedings of the Third European Tangible Interaction Studio (ETIS)*, 2017.

[81] Leonardo Angelini, Denis Lalanne, Elise van den Hoven, Omar Abou Khaled, and Elena Mugellini. Move, hold and touch: a framework for tangible gesture interactive systems. *Machines*, 3(3):173–207, 2015.

[82] Leonardo Angelini, Zuzanna Lechelt, Eva Hornecker, Paul Marshall, Can Liu, Margot Brereton, Alessandro Soro, Nadine Couture, Omar Abou Khaled, and Elena Mugellini. Internet of tangible things: Workshop on tangible interaction with the internet of things. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, page W14. ACM, 2018.

[83] Alissa N Antle and Sijie Wang. Comparing motor-cognitive strategies for spatial problem solving with tangible and multi-touch interfaces. In *Proc. of TEI'13*, pages 65–72. ACM, 2013.

[84] Ahmed Sabbir Arif, Roozbeh Manshaei, Sean Delong, Brien East, Matthew Kyan, and Ali Mazalek. Sparse tangibles: Collaborative exploration of gene networks using active tangibles and interactive tabletops. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 287–295. ACM, 2016.

[85] Kikuo Asai, Hideaki Kobayashi, and Tomotsugu Kondo. Augmented instructions-a fusion of augmented reality and printed learning materials. In *Advanced Learning Technologies, 2005. ICALT 2005. Fifth IEEE International Conference on*, pages 213–215. IEEE, 2005.

[86] Saskia Bakker, Elise Hoven, and Berry Eggen. Peripheral interaction: characteristics and considerations. *Personal and Ubiquitous Computing*, 19(1):239–254, 2015.

[87] Saskia Bakker, Elise van den Hoven, and Berry Eggen. Fireflies: physical peripheral interaction design for the everyday routine of primary school teachers. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, pages 57–64. ACM, 2013.

[88] Saskia Bakker, Elise van den Hoven, Berry Eggen, and Kees Overbeeke. Exploring peripheral interaction design for primary school teachers. In *Proceedings of the sixth international conference on tangible, embedded and embodied interaction*, pages 245–252. ACM, 2012.

[89] Yoseph Bar-Cohen. Haptic devices for virtual reality, telepresence, and human-assistive robotics. *Biologically inspired intelligent robots*, 73, 2003.

[90] Michel Beaudouin-Lafon and Wendy Mackay. Prototyping tools and techniques. *Human Computer Interaction-Development Process*, pages 122–142, 2003.

[91] Ross Bencina and Martin Kaltenbrunner. The design and evolution of fiducials for the reactivision system. In *Proc. 3rd International Conference on Generative Systems in the Electronic Arts*, 2005.

[92] Andrea Bianchi and Ian Oakley. Magnid: Tracking multiple magnetic tokens. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 61–68. ACM, 2015.

[93] Mark Billinghurst, Hirokazu Kato, and Ivan Poupyrev. The magicbook-moving seamlessly between reality and virtuality. *IEEE Computer Graphics and applications*, 21(3):6–8, 2001.

[94] Geoffrey P Bingham and Christopher C Pagano. The necessity of a perception–action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance*, 24(1):145, 1998.

[95] Rachel Blagojevic, Xiliang Chen, Ryan Tan, Robert Sheehan, and Beryl Plimmer. Using tangible drawing tools on a capacitive multi-touch display. In *Proceedings of the 26th Annual BCS Interaction Specialist Group Conference on People and Computers*, pages 315–320. British Computer Society, 2012.

[96] Q David Bowers. *Encyclopedia of automatic musical instruments*. Vestal Press, 1972.

[97] George S Carr. Formulas and theorems in pure mathematics. 1970.

[98] Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. Capstones and zebrawidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2189–2192. ACM, 2012.

[99] Barbara S Chaparro, Mikki H Phan, Christina Siu, and Jo R Jardina. User performance and satisfaction of tablet physical keyboards. *Journal of Usability Studies*, 9(2):70–80, 2014.

[100] Jaehee Cho, Yeongmin Won, Atit Kothari, Stephanie Fawaz, Zixu Ding, and Xu Cheng. Injustice: interactive live action virtual reality experience. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, pages 33–37. ACM, 2016.

[101] Jonathan Cohen, Meg Withgott, and Philippe Piernot. Logjam: a tangible multi-person interface for video logging. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 128–135. ACM, 1999.

[102] Jonathan Cohen, Meg Withgott, and Philippe Piernot. Logjam: a tangible multi-person interface for video logging. In *Proc. of CHI'99*, pages 128–135, 1999.

[103] Patricia Cohen, Stephen G West, and Leona S Aiken. *Applied multiple regression/correlation analysis for the behavioral sciences*. Psychology Press, 2014.

[104] Elizabeth S Collier and Rebecca Lawson. Its out of my hands! grasping capacity may not influence perceived object size. *Journal of Experimental Psychology: Human Perception and Performance*, 43(4):749, 2017.

[105] Wikimedia Commons. Airman's coin, 2001.

[106] Wikimedia Commons. Function table from eniac on display at aberdeen proving grounds museum., 2003.

[107] Wikimedia Commons. A sage (semi-automatic ground environment) terminal., 2007.

[108] Wikimedia Commons. Dial box made by silicon graphics inc, 2009.

[109] Roger Cook and Paul Fenn. Dynamic digital posters: Making the most of collaborative learning spaces. In *Proc. of 30th ascilite Conference," Electric Dreams"*, pages 195–200. ascilite, 2013.

[110] James E Cutting and Peter M Vishton. Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of space and motion*, pages 69–117. Elsevier, 1995.

[111] Carlos H de Brito Cruz and Luiz De Mello. Boosting innovation performance in brazil. 2006.

[112] R. De Simone, J. Rodrian, B. Osswald, F.-U. Sack, E. De Simone, and S. Hagl. Initial experience with a new communication tool: the 'digital interactive poster presentation'. *European Journal of Cardio-thoracic Surgery*, 19(6):953–955, 2001.

[113] Alexandre G de Siqueira, Brygg Ullmer, Mark Delarosa, Chris Branton, and Miriam K Konkel. Hard and soft tangibles: Mixing multi-touch and tangible interaction in scientific poster scenarios. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 476–486. ACM, 2018.

[114] Norman Donald. The design of everyday things. *Doubled Currency*, 1988.

[115] Pierre Dragicevic and Yvonne Jansen. List of physical visualizations. `http://dataphys.org/list/durrell-bishops-marble-answering-machine/`, Nov 2014. (Accessed on 08/26/2018).

[116] Page Dubois. Reading the writing on the wall. *Classical Philology*, 102(1):45–56, 2007.

[117] Patrick S Dukes, Austen Hayes, Larry F Hodges, and Michelle Woodbury. Punching ducks for post-stroke neurorehabilitation: System design and initial exploratory feasibility study. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 47–54. IEEE, 2013.

[118] Larissa DAngelo. From posters to e-posters: The evolution of a genre. *LANGUAGE*, 4:46–54, 2012.

[119] Elham Ebrahimi, Bliss Altenhoff, Leah Hartman, J Adam Jones, Sabarish V Babu, Christopher C Pagano, and Timothy A Davis. Effects of visual and proprioceptive information in visuo-motor calibration during a closed-loop physical reach task in immersive virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*, pages 103–110. ACM, 2014.

[120] Elham Ebrahimi, Bliss M Altenhoff, Christopher C Pagano, and Sabarish V Babu. Carryover effects of calibration to visual and proprioceptive information on near field distance judgments in 3d user interaction. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 97–104. IEEE, 2015.

[121] Elham Ebrahimi, Andrew Robb, Leah S Hartman, Christopher C Pagano, and Sabarish V Babu. Effects of anthropomorphic fidelity of self-avatars on reach boundary estimation in immersive virtual environments. In *Proceedings of the 15th ACM Symposium on Applied Perception*, page 2. ACM, 2018.

[122] Darren Edge and Alan F Blackwell. Peripheral tangible interaction by analytic design. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, pages 69–76. ACM, 2009.

[123] Douglas C Engelbart. The mother of all demos. 1968.

[124] Daniel Engelberg and Ahmed Seffah. A framework for rapid mid-fidelity prototyping of web sites. In *Usability*, pages 203–215. Springer, 2002.

[125] Thomas Erickson, N Sadat Shami, Wendy A Kellogg, and David W Levine. Synchronous interaction among hundreds: an evaluation of a conference in an avatar-based virtual environment. In *Proc. of CHI'11*, pages 503–512. ACM, 2011.

[126] Robert R Everett, Charles A Zraket, and Herbert D Benington. Sage: A data-processing system for air defense. In *Papers and discussions presented at the December 9-13, 1957, eastern joint computer conference: Computers with deadlines to meet*, pages 148–155. ACM, 1957.

[127] George W Fitzmaurice and William Buxton. *Graspable user interfaces.* University of Toronto, 1997.

[128] George W Fitzmaurice, Hiroshi Ishii, and William AS Buxton. Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 442–449. ACM Press/Addison-Wesley Publishing Co., 1995.

[129] Christiane Floyd. A systematic look at prototyping. In *Approaches to prototyping*, pages 1–18. Springer, 1984.

[130] Friedrich Froebel. *Pedagogics of the Kindergarten.* 1899.

[131] William W Gaver. Technology affordances. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 79–84. ACM, 1991.

[132] William W Gaver, John Bowers, Andrew Boucher, Hans Gellerson, Sarah Pennington, Albrecht Schmidt, Anthony Steed, Nicholas Villars, and Brendan Walker. The drift table: designing for ludic engagement. In *CHI'04 extended abstracts on Human factors in computing systems*, pages 885–900. ACM, 2004.

[133] Rosella Gennari, Alessandra Melonio, and Mehdi Rizvi. Evolving tangibles for children's social learning through conversations: Beyond turntalk. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 368–375. ACM, 2018.

[134] Renaud Gervais, Joan Sol Roo, and Martin Hachet. Tangible viewports: Getting out of flatland in desktop environments. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 176–184. ACM, 2016.

[135] James Jerome Gibson. The senses considered as perceptual systems. 1966.

[136] Daniel Harley, Aneesh P Tarun, Daniel Germinario, and Ali Mazalek. Tangible vr: Diegetic tangible objects for virtual reality narratives. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, pages 1253–1263. ACM, 2017.

[137] Larry F Hodges, Page Anderson, Grigore C Burdea, HG Hoffmann, and Barbara O Rothbaum. Treating psychological and phsyical disorders with vr. *IEEE Computer Graphics and Applications*, 21(6):25–33, 2001.

[138] Hunter G Hoffman. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No. 98CB36180)*, pages 59–63. IEEE, 1998.

[139] Lars Erik Holmquist, Johan Redström, and Peter Ljungstrand. Token-based access to digital information. In *International Symposium on Handheld and Ubiquitous Computing*, pages 234–245. Springer, 1999.

[140] Stephen Hood, Ralph Rabbat, Mihir Shah, Adam Durfee, Alastair Gourlay, Peter Anick, Richard Kasperski, Oliver Thomas Bayley, Ashley Woodman Hall, Shyam Kapur, et al. Speculative search result based on a not-yet-submitted search query, March 2 2010. US Patent 7,672,932.

[141] Jonathan Hook, Thomas Nappey, Steve Hodges, Peter Wright, and Patrick Olivier. Making 3d printed objects interactive using wireless accelerometers. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pages 1435–1440. ACM, 2014.

[142] Peter Hoonakker, Pascale Carayon, Ayse P Gurses, Roger Brown, Adjhaporn Khunlertkit, Kerry McGuire, and James M Walker. Measuring workload of icu nurses with a questionnaire survey: the nasa task load index (tlx). *IIE transactions on healthcare systems engineering*, 1(2):131–143, 2011.

[143] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. Physikit: Data engagement through physical ambient visualizations in the home. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1608–1619. ACM, 2016.

[144] Stephanie Houde and Charles Hill. What do prototypes prototype? In *Handbook of Human-Computer Interaction (Second Edition)*, pages 367–381. Elsevier, 1997.

[145] Glyn W Humphreys, Sanjay Kumar, Eun Young Yoon, Melanie Wulff, Katherine L Roberts, and M Jane Riddoch. Attending to the possibilities of action. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1628):20130059, 2013.

[146] Edwin Hutchins. *Cognition in the Wild*. MIT press, 1995.

[147] Victoria Interrante, Brian Ries, and Lee Anderson. Distance perception in immersive virtual environments, revisited. In *IEEE Virtual Reality Conference (VR 2006)*, pages 3–10. IEEE, 2006.

[148] Scott Isensee and James Rudd. The art of rapid prototyping: User interface design for windows and os/2. *Interactions-New York*, 3(2):79, 1996.

[149] Hiroshi Ishii, Daniel Leithinger, Sean Follmer, Amit Zoran, Philipp Schoessler, and Jared Counts. Transform: Embodiment of radical atoms at milano design week. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, pages 687–694. ACM, 2015.

[150] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, pages 234–241. ACM, 1997.

[151] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. Tangible remote controllers for wall-size displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2865–2874. ACM, 2012.

[152] Hans-Christian Jetter, Jens Gerken, Michael Zöllner, Harald Reiterer, and Natasa Milic-Frayling. Materializing the query with facet-streams: a hybrid surface for collaborative search on tabletops. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3013–3022. ACM, 2011.

[153] J. Johnson, T.L. Roberts, W. Verplank, D.C. Smith, C.H. Irby, M. Beard, and K. Mackey. The Xerox Star: a retrospective. *Computer*, 22(9):11 –26, Sep. 1989.

[154] J Adam Jones, J Edward Swan II, Gurjot Singh, and Stephen R Ellis. Peripheral visual information and its effect on distance judgments in virtual and augmented environments. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, pages 29–36. ACM, 2011.

[155] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. The reactable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proceedings of the 1st international conference on Tangible and embedded interaction*, pages 139–146. ACM, 2007.

[156] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proc. of TEI'07*, pages 139–146. ACM, 2007.

[157] Sungchul Jung, Gerd Bruder, Pamela J Wisniewski, Christian Sandor, and Charles E Hughes. Over my hand: Using a personalized hand in vr to improve object size estimation, body ownership, and presence. In *Proceedings of the Symposium on Spatial User Interaction*, pages 60–68. ACM, 2018.

[158] Martin Kaltenbrunner and Ross Bencina. reactivision: a computer-vision framework for table-based tangible interaction. In *Proceedings of the 1st international conference on Tangible and embedded interaction*, pages 69–74. ACM, 2007.

[159] Martin Kaltenbrunner, Till Bovermann, Ross Bencina, and Enrico Costanza. Tuio: A protocol for table-top tangible user interfaces. In *Proc. of the The 6th Intl Workshop on Gesture in Human-Computer Interaction and Simulation*, pages 1–5, 2005.

[160] Dietrich Kammer, Jan Wojdziak, Mandy Keck, Rainer Groh, and Severin Taranko. Towards a formalization of multi-touch gestures. In *Proc. of ITS'10*, pages 49–58. ACM, 2010.

[161] H Kato, M Billinghurst, I Poupyrev, N Tetsutani, and K Tachibana. Tangible augmented reality for human computer interaction. In *Proceedings of Nicograph 2001*, 2001.

[162] Jonathan W Kelly, William W Hammel, Zachary D Siegel, and Lori A Sjolund. Recalibration of perceived distance in virtual environments occurs rapidly and transfers asymmetrically across scale. *IEEE transactions on visualization and computer graphics*, 20(4):588–595, 2014.

[163] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[164] Lynch Kevin. The image of the city. *Cambridge Massachussettes*, 1960.

[165] David Kirk, Abigail Sellen, Stuart Taylor, Nicolas Villar, and Shahram Izadi. Putting the physical into the digital: issues in designing hybrid interactive surfaces. In *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*, pages 35–44. British Computer Society, 2009.

[166] Jack Loomis Joshua Knapp. Visual perception of egocentric distance in real and virtual environments. In *Virtual and adaptive environments*, pages 35–60. CRC Press, 2003.

[167] REZA KORMI-NOURI, LARS-GÖRAN NILSSON, and Nobuo Ohta. The novelty effect: Support for the novelty-encoding hypothesis. *Scandinavian journal of psychology*, 46(2):133–143, 2005.

[168] Daria Kotys-Schwartz and Mark E Rentschler. What is a prototype? what are the roles of prototypes in companies?

[169] P Venkata Krishna. *Challenges, Opportunities, and Dimensions of Cyber-Physical Systems*. IGI Global, 2014.

[170] Benjamin R Kunz, Sarah H Creem-Regehr, and William B Thompson. Does perceptual-motor calibration generalize across two different forms of locomotion? investigations of walking and wheelchairs. *PloS one*, 8(2):e54446, 2013.

[171] E. Lee. Cyber physical systems: Design challenges. In *Proc. of ISORC'08*, pages 363–369, 2008.

[172] Gun A Lee, Claudia Nelles, Mark Billinghurst, and Gerard Jounghyun Kim. Immersive authoring of tangible augmented reality applications. In *Proceedings of the 3rd IEEE/ACM international Symposium on Mixed and Augmented Reality*, pages 172–181. IEEE Computer Society, 2004.

[173] Jay Lee, Behrad Bagheri, and Hung-An Kao. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3:18–23, 2015.

[174] Jinha Lee, Alex Olwal, Hiroshi Ishii, and Cati Boulanger. Spacetop: integrating 2d and spatial 3d interactions in a see-through desktop environment. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 189–192. ACM, 2013.

[175] Spencer J Lee, Edward A Fox, Gary Marchionini, Javier Velacso, Gonçalo Antunes, and José Borbinha. Virtual DL poster sessions in Second Life. In *Proc. of Digital Libraries'09*, pages 473–474. ACM, 2009.

[176] Youn-Kyung Lim, Erik Stolterman, and Josh Tenenberg. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 15(2):7, 2008.

[177] Sally A Linkenauger, Markus Leyrer, Heinrich H Bülthoff, and Betty J Mohler. Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PloS one*, 8(7):e68594, 2013.

[178] Sally A Linkenauger, Veronica Ramenzoni, and Dennis R Proffitt. Illusory shrinkage and growth: Body-based rescaling affects the perception of size. *Psychological Science*, 21(9):1318–1325, 2010.

[179] Sally A Linkenauger, Jessica K Witt, and Dennis R Proffitt. Taking a hands-on approach: apparent grasping ability scales the perception of object size. *Journal of Experimental Psychology: Human Perception and Performance*, 37(5):1432, 2011.

[180] Daniel Livingstone and Jeremy Kemp. Integrating web-based and 3d learning environments: Second life meets moodle. *CEPIS UPGRADE: European Journal for the Informatics Professional*, 2008(3):8–14, 2008.

[181] Diana Löffler, Robert Tscharn, and Jörn Hurtienne. Multimodal effects of color and haptics on intuitive interaction with tangible user interfaces. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 647–655. ACM, 2018.

[182] Jock D Mackinlay, George G Robertson, and Stuart K Card. The perspective wall: Detail and context smoothly integrated. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 173–176. ACM, 1991.

[183] Karon E MacLean, Scott S Snibbe, and Golan Levin. Tagged handles: merging discrete and continuous manual control. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 225–232. ACM, 2000.

[184] Veera Bhadra Harish Mandalika, Alexander I Chernoglazov, Mark Billinghurst, Christoph Bartneck, Michael A Hurrell, Niels de Ruiter, Anthony PH Butler, and Philip H Butler. A hybrid 2d/3d user interface for radiological diagnosis. *Journal of Digital Imaging*, pages 1–18, 2017.

[185] R. Marx. *Masters of the Poster, 1896-1900.* Academy Publications, 1977. p. 7.

[186] David Mathias, Ben Hicks, Chris Snider, Charlie Ranscombe, et al. Characterising the affordances and limitations of common prototyping techniques to support the early stages of product develpment. In *DS92: Proceedings of the DESIGN 2018 15th International Design Conference*, pages 1257–1268, 2018.

[187] Ali Mazalek, Glorianna Davenport, and Hiroshi Ishii. Tangible viewpoints: a physical approach to multimedia stories. In *Proceedings of the tenth ACM international conference on Multimedia*, pages 153–160. ACM, 2002.

[188] Ali Mazalek and Michael Nitsche. Tangible interfaces for real-time 3d virtual environments. In *Proceedings of the international conference on Advances in computer entertainment technology*, pages 155–162. ACM, 2007.

[189] Ali Mazalek, Orit Shaer, Brygg Ullmer, Miriam K Konkel, et al. Tangible meets gestural: Gesture based interaction with active tokens. In *Proc. of CHI'14*. ACM, 2014.

[190] Michael McCurdy, Christopher Connors, Guy Pyrzak, Bob Kanefsky, and Alonso Vera. Breaking the fidelity barrier: an examination of our current characterization of prototypes and an example of a mixed-fidelity success. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 1233–1242. ACM, 2006.

[191] Joanna McGrenere and Wayne Ho. Affordances: Clarifying and evolving a concept. In *Graphics interface*, volume 2000, pages 179–186, 2000.

[192] Marshall McLuhan and Quentin Fiore. The medium is the message. *New York*, 123:126–128, 1967.

[193] David A Mellis, Dana Gordon, and Leah Buechley. Fab fm: the design, making, and modification of an open-source electronic product. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, pages 81–84. ACM, 2011.

[194] David Merrill, Emily Sun, and Jeevan Kalanithi. Sifteo cubes. In *CHI'12 Extended Abstracts on Human Factors in Computing Systems*, pages 1015–1018. ACM, 2012.

[195] Paul Milgram and Fumio Kishino. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329, 1994.

[196] Betty J Mohler, Sarah H Creem-Regehr, and William B Thompson. The influence of feedback on egocentric distance judgments in real and virtual environments. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization*, pages 9–14. ACM, 2006.

[197] Aaron Moore. Lithium polymer (lipo) battery guide. *ProtoTalk. net*, 2008.

[198] Rafael Morales González, Caroline Appert, Gilles Bailly, and Emmanuel Pietriga. Touchtokens: Guiding touch patterns with passive tokens. In *Proc. of CHI'16*, pages 4189–4202. ACM, 2016.

[199] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. Wireprint: 3d printed previews for fast prototyping. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*, pages 273–280. ACM, 2014.

[200] Stefanie Mueller, Tobias Mohr, Kerstin Guenther, Johannes Frohnhofen, and Patrick Baudisch. fabrickation: fast 3d printing of functional objects by integrating construction kit building blocks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3827–3834. ACM, 2014.

[201] Brad Myers, Scott E Hudson, and Randy Pausch. Past, present, and future of user interface software tools. *TOCHI'00*, 7(1):3–28, 2000.

[202] C David Navarrete, Melissa M McDonald, Michael L Mott, and Benjamin Asher. Virtual morality: Emotion and action in a simulated three-dimensional trolley problem. *Emotion*, 12(2):364, 2012.

[203] Hans Neukom. The second life of eniac. *IEEE Annals of the History of Computing*, 28(2):4–16, 2006.

[204] H. Neundorf. Turkish archaeologists discover the world's oldest known writings. `https://news.artnet.com/art-world/turkey-worlds-oldest-writing-pictograph-319107`. (Accessed on 07/18/2017).

[205] Neuroscience. Neuroscience 2015 annual conference poster abstracts. `https://www.sfn.org/Annual-Meeting/Neuroscience-2015/Sessions-and-Events/Program/Abstract-PDFs-2015`. (Accessed on 07/10/2017).

[206] William Odom, Ron Wakkary, Youn-kyung Lim, Audrey Desjardins, Bart Hengeveld, and Richard Banks. From research prototype to research product. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 2549–2561. ACM, 2016.

[207] Nami Ogawa, Yuki Ban, Sho Sakurai, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. Metamorphosis hand: dynamically transforming hands. In *Proceedings of the 7th Augmented Human International Conference 2016*, page 51. ACM, 2016.

[208] Nami Ogawa, Takuji Narumi, and Michitaka Hirose. Distortion in perceived size and body-based scaling in virtual environments. In *Proceedings of the 8th Augmented Human International Conference*, page 35. ACM, 2017.

[209] Kerem Ok, Vedat Coskun, Mehmet N Aydin, and Busra Ozdenizci. Current benefits and future directions of nfc services. In *Education and Management Technology (ICEMT), 2010 International Conference on*, pages 334–338. IEEE, 2010.

[210] James Patten, Hiroshi Ishii, Jim Hines, and Gian Pangaro. Sensetable: a wireless object tracking platform for tangible user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 253–260. ACM, 2001.

[211] Rhianna K Pedwell, James A Hardy, and Susan L Rowland. Effective visual design and communication practices for research posters: Exemplars based on the theory and practice of multimedia learning and rhetoric. *Biochemistry and Molecular Biology Education*, 45(3):249–261, 2017.

[212] Eujin Pei, Garrett W Melenka, Jonathon S Schofield, Michael R Dawson, and Jason P Carey. Evaluation of dimensional accuracy and material properties of the makerbot 3d desktop printer. *Rapid Prototyping Journal*, 2015.

[213] M. Petre. Why looking isn't always seeing: Readership skills and graphical programming. *Communications of the ACM*, 38:33–44, June 1995.

[214] Ken Pfeuffer and Hans Gellersen. Gaze and touch interaction on tablets. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 301–311. ACM, 2016.

[215] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E Robinson. Project jacquard: interactive digital textiles at scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 4216–4227. ACM, 2016.

[216] Dennis R Proffitt and Sally A Linkenauger. Perception viewed as a phenotypic expression. *Action science: Foundations of an emerging discipline*, 171, 2013.

[217] Joseph Psotka. Immersive training systems: Virtual reality and education and training. *Instructional science*, 23(5-6):405–431, 1995.

[218] Amanda Purington, Jessie G Taft, Shruti Sannon, Natalya N Bazarova, and Samuel Hardman Taylor. Alexa is my new bff: social roles, user satisfaction, and personification of the amazon echo. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 2853–2859. ACM, 2017.

[219] JW Regian, Wayne L Shebilske, and John M Monk. Virtual reality: an instructional medium for visual-spatial tasks. *Journal of Communication*, 42(4):136–149, 1992.

[220] S. Reichwein. *Die Litfaßsäule*. Presse-und Informationsamt des Landes Berlin, 1980.

[221] Jun Rekimoto. Pick-and-drop: a direct manipulation technique for multiple computer environments. In *Proc. of UIST'97*, pages 31–39. ACM, 1997.

[222] Jun Rekimoto. Smartskin: an infrastructure for freehand manipulation on interactive surfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 113–120. ACM, 2002.

[223] Rebekka S Renner, Boris M Velichkovsky, and Jens R Helmert. The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2):23, 2013.

[224] Adam R Richardson and David Waller. The effect of feedback training on distance estimation in virtual environments. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, 19(8):1089–1108, 2005.

[225] John J Rieser, Herbert L Pick, Daniel H Ashmead, and Anne E Garing. Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance*, 21(3):480, 1995.

[226] George G Robertson, Jock D Mackinlay, and Stuart K Card. Cone trees: animated 3d visualizations of hierarchical information. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 189–194. ACM, 1991.

[227] Irvin Rock and Jack Victor. Vision and touch: An experimentally created conflict between the two senses. *Science*, 143(3606):594–596, 1964.

[228] A Rose. Lightning strikes mathematics: Eniac. *Popular Science*, 148:83–86, 1946.

[229] Beat Rossmy and Alexander Wiethoff. Comb: A modular low-resolution display to support electronic musical pre-education. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, page 24. ACM, 2018.

[230] N. Rowe. Poster presentation -what to do with the 'elephant in the room'? In *6th Nordic Conference on Adult Education and Learning*, 2015.

[231] Nicholas Rowe and Dragan Ilic. What impact do posters have on academic knowledge transfer? a pilot survey on author attitudes and experiences. *BMC medical education*, 9(1):1, 2009.

[232] Jim Rudd, Ken Stern, and Scott Isensee. Low vs. high-fidelity prototyping debate. *interactions*, 3(1):76–85, 1996.

[233] Frank Ruskey and Mark Weston. A survey of venn diagrams. *Electronic Journal of Combinatorics*, 4:3, 1997.

[234] Mitsuyoshi Sato, Takumi Okamura, and Kaoru Kimura. Cyanoacrylate compositions, June 6 1989. US Patent 4,837,260.

[235] D. Schmandt-Besserat. *When Writing Met Art: From Symbol to Story.* University of Texas Press.

[236] Albrecht Schmidt. *Ubiquitous computing-computing in context.* PhD thesis, Lancaster University, 2003.

[237] Bertrand Schneider, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. Benefits of a tangible interface for collaborative learning and interaction. *IEEE Transactions on Learning Technologies*, 4(3):222–232, 2011.

[238] Bertrand Schneider, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. Benefits of a tangible interface for collaborative learning and interaction. *IEEE Transactions on Learning Technologies*, 4(3):222–232, 2011.

[239] Neal E Seymour. Vr to or: a review of the evidence that virtual reality simulation improves operating room performance. *World journal of surgery*, 32(2):182–188, 2008.

[240] Saya Shacham. A shortened version of the profile of mood states. *Journal of personality assessment*, 47(3):305–306, 1983.

[241] Reza Shadmehr, Maurice A Smith, and John W Krakauer. Error correction, sensory prediction, and adaptation in motor control. *Annual review of neuroscience*, 33:89–108, 2010.

[242] Orit Shaer and Eva Hornecker. Tangible User Interfaces: past, present, and future directions. *Found. Trends Hum.-Comput. Interact.*, 3(1–2):1–137, January 2010.

[243] Orit Shaer, Eva Hornecker, et al. Tangible user interfaces: past, present, and future directions. *Foundations and Trends® in Human–Computer Interaction*, 3(1–2):4–137, 2010.

[244] Orit Shaer and Robert JK Jacob. A specification paradigm for the design and implementation of tangible user interfaces. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(4):20, 2009.

[245] Orit Shaer, Nancy Leland, Eduardo H. Calvillo-Gamez, and Robert J. K. Jacob. The TAC paradigm: specifying tangible user interfaces. *Personal and Ubiquitous Computing*, 8(5):359–369, 2004.

[246] Orit Shaer, Nancy Leland, Eduardo H Calvillo-Gamez, and Robert JK Jacob. The tac paradigm: specifying tangible user interfaces. *Personal and Ubiquitous Computing*, 8(5):359–369, 2004.

[247] Andrew Singer, Debby Hindus, Lisa Stifelman, and Sean White. Tangible progress: less is more in somewire audio spaces. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 104–111. ACM, 1999.

[248] Mel Slater and Maria V Sanchez-Vives. Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI*, 3:74, 2016.

[249] Mel Slater and Anthony Steed. A virtual presence counter. *Presence: Teleoperators & Virtual Environments*, 9(5):413–434, 2000.

[250] Theremin Leo Ssergejewitsch. Method of and apparatus for the generation of sounds, February 28 1928. US Patent 1,661,058.

[251] Ivan E Sutherland. Sketch pad a man-machine graphical communication system. In *Proceedings of the SHARE design automation workshop*, pages 6–329. ACM, 1964.

[252] Hideyuki Suzuki and Hiroshi Kato. Algoblock: a tangible programming language, a tool for collaborative learning. In *Proceedings of 4th European Logo Conference*, pages 297–303, 1993.

[253] Pygmal Technologies. Space. `https://getspace.io/#faq`, Dec. 2017. (Accessed on 12/01/2017).

[254] Judith Jarvis Thomson. Killing, letting die, and the trolley problem. *The Monist*, 59(2):204–217, 1976.

[255] Yuki Tsujimoto, Yuichi Itoh, and Takao Onoye. Ketsuro-graffiti: An interactive display with water condensation. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces*, pages 49–55. ACM, 2016.

[256] B. Ullmer, H. Ishii, and R.J.K. Jacob. Token+constraint systems for tangible interaction with digital information. *TOCHI'05*, 12(1):81–118, 2005.

[257] Brygg Ullmer and Hiroshi Ishii. Emerging frameworks for tangible user interfaces. *IBM systems journal*, 39(3.4):915–931, 2000.

[258] Brygg Ullmer, Hiroshi Ishii, and Robert JK Jacob. Tangible query interfaces: Physically constrained tokens for manipulating database queries. In *Proc. of INTERACT*, volume 3, pages 279–286, 2003.

[259] Brygg Ullmer, Hiroshi Ishii, and Robert JK Jacob. Token+ constraint systems for tangible interaction with digital information. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 12(1):81–118, 2005.

[260] Brygg Ullmer, Elizabeth Kim, Axel Kilian, Steve Gray, and Hiroshi Ishii. Strata/icc: physical models as computational interfaces. In *CHI'01 Extended Abstracts on Human Factors in Computing Systems*, pages 373–374. ACM, 2001.

[261] Brygg Ullmer, Alexandre Siqueira, Chris Branton, and Miriam K Konkel. Weaving peripheral interaction within habitable architectures. In *Peripheral Interaction*, pages 253–272. Springer, 2016.

[262] Brygg Ullmer, Blake Tregre, and Malcolm McClay. Framing fraught topics through tangible multi-display engagement with live news. In *Proceedings of the 6th ACM International Symposium on Pervasive Displays*, page 1. ACM, 2017.

[263] Brygg Anders Ullmer and Hiroshi Ishii. *Tangible interfaces for manipulating aggregates of digital information*. PhD thesis, Citeseer, 2002.

[264] Consuelo Valdes, Diana Eastman, Casey Grote, Shantanu Thatte, Orit Shaer, Ali Mazalek, Brygg Ullmer, and Miriam K Konkel. Exploring the design space of gestural interaction with active tokens through user-defined gestures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 4107–4116. ACM, 2014.

[265] James Vallino and Christopher Brown. Haptics in augmented reality. In *Multimedia Computing and Systems, 1999. IEEE International Conference on*, volume 1, pages 195–200. IEEE, 1999.

[266] HV Vinters, KA Galil, MJ Lundie, and JCE Kaufmann. The histotoxicity of cyanoacrylates. *Neuroradiology*, 27(4):279–291, 1985.

[267] Mathieu Virbel, Thomas E Hansen, and Oleksandr Lobunets. Kivy-a framework for rapid creation of innovative user interfaces. In *Proc. of Mensch & Computer Workshopband*, pages 69–73, 2011.

[268] Robert A Virzi, Jeffrey L Sokolov, and Demetrios Karis. Usability problem identification using both low-and high-fidelity prototypes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 236–243. ACM, 1996.

[269] Simon Voelker, Kosuke Nakajima, Christian Thoresen, Yuichi Itoh, Kjell Ivar Øvergård, and Jan Borchers. Pucs: detecting transparent, passive untouched capacitive widgets on unmodified multi-touch displays. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces*, pages 101–104. ACM, 2013.

[270] Hermann Von Helmholtz. *Handbuch der physiologischen Optik*, volume 9. Voss, 1867.

[271] Ioannis Vrellis, Nikolaos Avouris, and Tassos A Mikropoulos. Learning outcome, presence and satisfaction from a science activity in second life. *Australasian Journal of Educational Technology*, 32(1), 2016.

[272] Roy Want and Daniel M Russell. Ubiquitous electronic tagging. *IEEE Distributed Systems Online*, (2):null, 2000.

[273] Gareth Watson, Sebastien Brault, Richard Kulpa, Benoit Bideau, Joe Butterfield, and Cathy Craig. Judging the passabilityof dynamic gaps in a virtual rugby environment. *Human Movement Science*, 30(5):942–956, 2011.

[274] Webometrics. Ranking web of universities. `http://www.webometrics.info/en/About_Us`, 2015.

[275] Ina Wechsung, Klaus-Peter Engelbrecht, Anja Naumann, Sebastian Möller, Stefan Schaffer, and Robert Schleicher. Investigating modality selection strategies. In *Proc. of SLT'10*, pages 31–36. IEEE, 2010.

[276] Ina Wechsung, Robert Schleicher, and Sebastian Möller. How context determines perceived quality and modality choice. secondary task paradigm applied to the evaluation of multimodal interfaces. In *Proc. of Paralinguistic Information and its Integration in Spoken Dialogue Systems Workshop*, pages 327–340. Springer, 2011.

[277] Mark Weiser. The computer for the 21st century. *Scientific american*, 265(3):94–104, 1991.

[278] Mark Weiser. The computer for the 21st century: specialized elements of hardware and software, connected by wires, radio waves and infrared, will be so ubiquitous that no one will notice their presence. In *Readings in Human–Computer Interaction*, pages 933–940. Elsevier, 1995.

[279] Mark Weiser and John Seely Brown. Designing calm technology. *PowerGrid Journal*, 1(1):75–85, 1996.

[280] Malte Weiss, Roger Jennings, Ramsin Khoshabeh, Jan Borchers, Julie Wagner, Yvonne Jansen, and James D Hollan. Slap widgets: bridging the gap between virtual and physical controls on tabletops. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*, pages 3229–3234. ACM, 2009.

[281] Pierre David Wellner. Interacting with paper on the digitaldesk. Technical report, University of Cambridge, Computer Laboratory, 1994.

[282] Stephan Wensveen and Ben Matthews. Prototypes and prototyping in design research. *Routledge companion to design research*, pages 262–276, 2015.

[283] Sean White, David Feng, and Steven Feiner. Interaction and presentation techniques for shake menus in tangible augmented reality. In *Mixed and Augmented Reality, 2009. ISMAR 2009. 8th IEEE International Symposium on*, pages 39–48. IEEE, 2009.

[284] Frederik Wiehr, Alexandra Voit, Dominik Weber, Sven Gehring, Christoph Witte, Daniel Kärcher, Niels Henze, and Antonio Krüger. Challenges in designing and implementing adaptive ambient notification environments. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, pages 1578–1583. ACM, 2016.

[285] Alexander Wiethoff, Hanna Schneider, Michael Rohs, Andreas Butz, and Saul Greenberg. Sketch-a-tui: low cost prototyping of tangible interactions using cardboard and conductive ink. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, pages 309–312. ACM, 2012.

[286] Wikipedia. Cubism — wikipedia, the free encyclopedia, 2017. [Online; accessed 2-December-2017].

[287] Robin Williams. *The non-designer's design book: Design and typographic principles for the visual novice*. Pearson Education, 2015.

[288] Bob G Witmer and Paul B Kline. Judging perceived and traversed distance in virtual environments. *Presence*, 7(2):144–167, 1998.

[289] Bob G Witmer and Michael J Singer. Measuring presence in virtual environments: A presence questionnaire. *Presence*, 7(3):225–240, 1998.

[290] Jacob O Wobbrock, Meredith Ringel Morris, and Andrew D Wilson. User-defined gestures for surface computing. In *Proc. of CHI'09*, pages 1083–1092. ACM, 2009.

[291] Katrin Wolf, Stefan Schneegass, Niels Henze, Dominik Weber, Valentin Schwind, Pascal Knierim, Sven Mayer, Tilman Dingler, Yomna Abdelrahman, Thomas Kubitza, et al. Tuis in the large: Using paper tangibles with mobile devices. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, pages 1579–1584. ACM, 2015.

[292] C. Woods. Visible language: the earliest writing systems. *Visible Language: Inventions of Writing in the Ancient Middle East and Beyond. The Oriental Institute of the University of Chicago, Chicago*, pages 15–25, 2010.

[293] Matthew Wright. Open sound control: an enabling technology for musical networking. *Organised Sound*, 10(03):193–200, 2005.

[294] Andy Wu, Derek Reilly, Anthony Tang, and Ali Mazalek. Tangible navigation and object manipulation in virtual environments. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, pages 37–44. ACM, 2011.

[295] Lesley Xie, Alissa N Antle, and Nima Motamedi. Are tangibles more fun?: comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In *Proc. of TEI'08*, pages 191–198. ACM, 2008.

[296] Neng-Hao Yu, Li-Wei Chan, Lung-Pan Cheng, Mike Y Chen, and Yi-Ping Hung. Enabling tangible interaction on capacitive touch panels. In *Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*, pages 457–458. ACM, 2010.

[297] Neng-Hao Yu, Li-Wei Chan, Seng Yong Lau, Sung-Sheng Tsai, I-Chun Hsiao, Dian-Je Tsai, Fang-I Hsiao, Lung-Pan Cheng, Mike Chen, Polly Huang, et al. Tuic: enabling tangible interaction on capacitive multi-touch displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2995–3004. ACM, 2011.

[298] Bieke Zaman, Vero Vanden Abeele, Panos Markopoulos, and Paul Marshall. the evolving field of tangible interaction for children: the challenge of empirical validation. *Personal and Ubiquitous Computing*, 16(4):367–378, 2012.

[299] Cheng Zhang, AbdelKareem Bedri, Gabriel Reyes, Bailey Bercik, Omer T Inan, Thad E Starner, and Gregory D Abowd. Tapskin: Recognizing on-skin input for smartwatches. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces*, pages 13–22. ACM, 2016.

[300] ZhiYing Zhou, Adrian David Cheok, TingTing Chan, Jiun Horng Pan, and Yu Li. Interactive entertainment systems using tangible cubes. In *IE2004: Proceedings of the First Australian Workshop on Interactive Entertainment*, page 19, 2004.

[301] Christine J Ziemer, Mia J Branson, Benjamin J Chihak, Joseph K Kearney, James F Cremer, and Jodie M Plumert. Manipulating perception versus action in recalibration tasks. *Attention, Perception, & Psychophysics*, 75(6):1260–1274, 2013.

[302] Thomas G Zimmerman, Joshua R Smith, Joseph A Paradiso, David Allport, and Neil Gershenfeld. Applying electric field sensing to human-computer interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 280–287. ACM Press/Addison-Wesley Publishing Co., 1995.