Behind Space

through movement and embodiment
in human-computer interaction

by

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Digital Version

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Dedication

The beginning of my career as a scholar was the day when I met and started working with Prof. Oğuzhan Özcan, a true visionary whose impact on design and technology research in Turkey cannot be overstated. Working with him has taught me the value of courage, ambition, and perseverance.

The final years of my PhD were supported by Qualisys AB, where I worked closely with Fredrik Müller—the company's chief executive, and perhaps more accurately, its father, pillar, and sage. Working with him has taught me the value of humility and generosity, and the true meaning of being "human-centered."

I dedicate my PhD thesis to Oğuzhan Özcan and Fredrik Müller. The vast majority of what I have accomplished professionally so far has been inspired and enabled by them. I only aspire, in the future, to lead and support people in the same way as they have done for me.

Abstract

How might we enjoy the benefits afforded by computers, and experience an abundance of physical experiences while doing so? This question has intrigued human-computer interaction (HCI) and interaction design (IxD) scholars since the inception of technologies like augmented reality and gesture sensing. Yet, despite abundant discourse and a stream of technologies to match, the vision of physical diversity in HCI is still not realized beyond research and niche applications. To address this issue, this dissertation presents a critique on and implications for the trajectories of technologies and discourse aimed at enriching the physicality of HCI, based on reflections on a compilation of five research publications. These publications report on: (1) an empirical study on the spectator experience in live electronic music; (2) an introductory educational program pertaining to user interface design with emerging technologies; (3) an augmented reality application for professional use; (4) a philosophical and conceptual exposition on design with emerging technologies and traditional craft; and (5) a literature review and design directions for interactive autonomous drones. A vocabulary of five notions distilled from the literature on embodied HCI, substantiated through reflections on the five projects, emerges as a principal contribution with the potential to inform future designs.

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I began my career as an academic researcher in Istanbul at the Koç University Design Lab, which later grew into the Koç University – Arçelik Research Center for Creative Industries (KUAR) under the direction of Prof. Oğuzhan Özcan. I then became part of Qualisys AB and Chalmers University of Technology's t2i Interaction Lab in Gothenburg. My numerous colleagues and friends at these institutions have been a continuous source of inspiration and motivation to me throughout this adventure. I look forward to a lifetime of friendships and professional collaborations with them.

The personnel at Koç University's College and Graduate School of Social Sciences and Humanities have been instrumental in enabling my work. In particular, without the support of Prof. Zeynep Aycan, the former director of the GSSSH, and Tuğçe Şatana, the school's coordinator, this thesis would not exist in its present form.

Most importantly, I thank my mother and father, for everything. My mother was a teacher, and she carried me lecturing in front of a classroom, before I was born. My father taught and encouraged me to read, before I even stepped into a school. I don't know what I'd be doing if they hadn't done what they did, but I'm pretty sure it wouldn't involve a PhD.

Notice of Prior Publication

This thesis is based on the following peer-reviewed publications:

Baytaş, M.A., Çay, D., Zhang, Y., Obaid, M., Yantaç, A.E., & Fjeld, M. (2019). The Design of Social Drones: A Review of Studies on Autonomous Flyers in Inhabited Environments. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI 2019).

Baytaş, M.A., Coşkun, A., Yantaç, A.E., & Fjeld, M. (2018). Towards Materials for Computational Heirlooms: Blockchains and Wristwatches. In *Proceedings of the 2018 Conference on Designing Interactive Systems* (DIS 2018).

Baytaş, M.A., Yantaç, A.E., & Fjeld, M. (2017). LabDesignAR: Configuring Multi-camera Motion Capture Systems in Augmented Reality. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (VRST '17).

Ünlüer, A. A., Baytaş, M. A., Buruk, O. T., Cemalcilar, Z., Yemez, Y., & Özcan, O. (2017). The Effectiveness of Mime-Based Creative Drama Education for Exploring Gesture-Based User Interfaces. *International Journal of Art & Design Education*.

Baytaş, M.A., Göksun, T., & Özcan, O. (2016). The Perception of Live-sequenced Electronic Music via Hearing and Sight. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (NIME 2016).

During the work reported in this thesis, the author has also produced the following peer-reviewed publications:

La Delfa, J., Baytaş, M.A., Wichtowski, O., Khot, R.A. & Mueller, F. (2019). Are Drones Meditative? In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI EA '19).

Baytaş, M.A. (2019). Religion for Machines: Humanism and Dataism as Perspectives on the Design of Machine Learning Systems. In *Proceedings of the CHI 2019 workshop "Emerging Perspectives in Human-Centered Machine Learning"*.

Baytaş, M.A., Coşkun, A., Yantaç, A.E., & Fjeld, M. (2019). Appreciating Digital Materials for Longevous Computational Artifacts. In *Proceedings of the CHI 2019 workshop "Towards a Responsible Innovation Agenda for HCI"*.

Baytaş, M.A., Obaid, M., La Delfa, J., Yantaç, A.E., & Fjeld. M. (2019). Integrated Apparatus for Empirical Studies with Embodied Autonomous Social Drones. In *Proceedings of the International Workshop on Human-Drone Interaction* (iHDI).

Baytaş, M.A., Çay, D., Thrash, T., Yantaç, A.E., & Fjeld, M. (2019). Towards Scalability in Empirical Studies on Nonverbal Communication through Augmented Reality and Motion Digitization. Poster presented at the *DComm* conference *Deictic Communication – Theory and Application*.

İnce, C., Toka, M., & Baytaş, M.A. (2018). Siren: Interface for Pattern Languages. In *Proceedings of the 2018 International Conference on New Interfaces for Musical Expression* (NIME 2018).

Baytaş, M.A., Batis, E., Bylund, M., Çay, D., Yantaç, A.E., & Fjeld, M. (2017). ViewFinder: Supporting the Installation and Reconfiguration of Multi-Camera Motion Capture Systems with a Mobile Application. Poster presented at the *16th International Conference on Mobile and Ubiquitous Multimedia* (MUM 2017).

Baytaş, M.A., Çay, D., Yantaç, A.E. & Fjeld, M. (2017). Motion Capture in Gesture and Sign Language Research. Poster presented at the DComm conference *Language as a Form of Action*.

Contents

Introduction

THE CONTROLS ON THE AVERAGE USER'S SHOWER ARE PROBABLY BETTER HUMAN-ENGINEERED THAN THOSE OF THE COMPUTER ON WHICH FAR MORE TIME IS SPENT.

Buxton (1990)

Motivation

Compelling design practice and scholarship often hinge on somewhat grand motivations or visions[1] that have to do with changing the world "from its current state to a preferred state".[2] So before I talk about my work, I would like to introduce the vision that drives it, and refine its focus.

[1] Ishii, H., Leithinger, D., Yao, L., Follmer, S., and Ou, J. (2015). Vision-driven: Beyond tangible bits, towards radical atoms. In *CHI EA '15*. ACM

[2] Simon, H. A. (1969). *The Sciences of the Artificial*. MIT Press; and Zimmerman, J., Forlizzi, J., and Evenson, S. (2007). Research Through Design as a Method for Interaction Design Research in HCI. In *Proc. CHI '07*. ACM

Many of us spend a significant and increasing proportion of our lives interacting with computers. In return for our time and attention, these computers bestow us with some superpowers beyond the dreams of mythical gods.[3] Yet, the incredible variety of things we can perform on a computer physically feel the same, as they boil down to staring and poking at screens. This constrained physicality, to me, often gives way to a dissonant and unnerving experience.

[3] Harari, Y. N. (2016). *Homo Deus: A Brief History of Tomorrow*. Harvill Secker

I am not the first to notice this issue. Buxton, quoted above, puts it with humor, concision, and accuracy.[4] Others have been more elaborate:

[4] Buxton, W. (1990). There's More to Interaction Than Meets the Eye: Some Issues in Manual Input. In Preece, J., editor, *Human-Computer Interaction*, pages 122–137. Prentice Hall Press

> "One of the most sweeping — and unintended — transformations that the desktop computing paradigm has brought about is the extent to which the physical performance of work has homogenized. For certain activities, such as writing this paper, the keyboard interaction paradigm appropriately leverages our bimanual dexterity. But, with a keyboard and mouse interface, the use of our bodies for writing a paper is the same as for editing photographs. And playing music. And communicating with friends and family. And anything else that one might want computation for."[5]

[5] Klemmer, S. R., Hartmann, B., and Takayama, L. (2006). How Bodies Matter: Five Themes for Interaction Design. In *Proc. DIS '06*. ACM

And of course, the problem is quite obvious for comic artists as well as scholars and designers (see Figure 1).

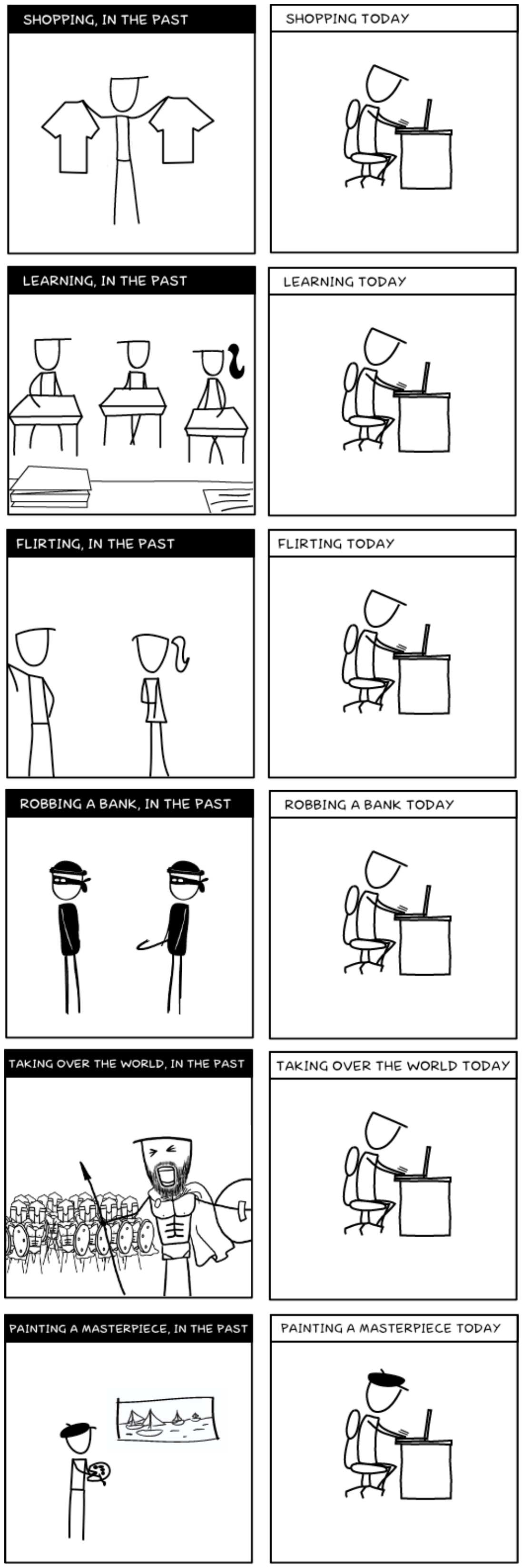

Figure 1: *Past And Present* by Doghouse Diaries (thedoghousediaries.com/3590) (CC BY-NC 4.0)

As we approach the end of the second decade in the 21st century, indeed, we are outgrowing the "desktop computing paradigm" which the above commentary focuses on. However, the touchscreen smartphones and tablets that are now pervasive in our lives do little to address the issue of physical homogeneity. Rather, the keyboard and mouse interface is simply being replaced by the touchscreen (see Figure 2)—not a particularly rich physical experience, nor an ergonomically favorable one.[6]

Figure 2: More recently, with "mobile technology" becoming pervasive, the physical experience depicted on Figure 1—sitting in front of a keyboard and display—has largely been replaced by another: staring down and poking at a touchscreen.

The vision, or first-order design challenge, that emerges from the above can be stated in the form of a question as follows: *How might we enjoy the productivity and amusement afforded by computers, and still experience an abundance of physical experiences while doing so?*

Focus

As stated above, the vision that I am putting forward—framed above as a design challenge—is not new. Over the last few decades, in tandem with technological developments, scholars in Human-Computer Interaction and Interaction Design (HCI/IxD) have produced a trove of inventions and discourse which speaks to how physical experience and the unity of the body and the mind figure in understanding and designing interactive computer systems. A seminal text in this body of work, for example, is Ishii and Ullmer's 1997 vision for "tangible bits"[7] where they propose to leverage "the richness of human senses and skills people have developed through a lifetime of interaction with the physical world" using a multitude of technologies including computer vision, projection mapping, robotics, and augmented reality. Another is Dourish's 2001 treatise[8] that integrates these technological concepts with philosophy and humanistic research approaches. In this literature, the central idea is that to understand, utilize, and serve the human body is imperative for good IxD. The concept of "embodiment" has a salient presence in the aforementioned discourse, where it relates to the instrumentality of the human body in perceiving and acting in the world, as well as unique qualities of other physical objects therein. Departing from these roots, a host of theoretical contributions with generative and evaluative potential were presented in academic literature (overviewed in the next chapter); which collectively serve the vision of physically rich HCI experiences.

Despite the abundant supply of discourse and a stream of technological developments to match, the vision of physical diversity in HCI experiences has still not been adopted widely beyond research projects and niche segments of the market for computing applications. This "current state" of the world prompts refining and reframing the

[6] Bachynskyi, M., Palmas, G., Oulasvirta, A., Steimle, J., and Weinkauf, T. (2015). Performance and ergonomics of touch surfaces: A comparative study using biomechanical simulation. In *Proc. CHI '15*. ACM

[7] Ishii, H. and Ullmer, B. (1997). Tangible bits: Towards seamless interfaces between people, bits and atoms. In *Proc. CHI '97*. ACM

[8] Dourish, P. (2001). *Where the action is: the foundations of embodied interaction*. MIT press

aforementioned design challenge to focus on the following questions:

- How does the discourse on movement and embodiment in HCI literature towards creating diverse physicality in HCI speak to current emerging technologies that are on their way to commodification?
- How can we articulate the potentials and shortcomings of the current technological and theoretical landscape, in order to serve the next generation of solutions which might enrich the physicality of HCI?

Format and Contributions

Aiming to address the questions above, I present a portfolio of five discrete research projects in this dissertation; each informed by the discourse on movement and embodiment in HCI/IxD literature and driven by serving the vision of diverse physicality in HCI. Each of these projects investigates and/or proposes HCI designs or related scaffolding that foreground movement and embodiment, while dealing with distinct technologies, application domains, methodologies, and research contributions.

In addition, before presenting the research projects—each previously reported in peer-reviewed HCI/IxD publications—I derive a vocabulary of salient notions from the HCI/IxD literature on movement and embodiment. Using this vocabulary, I reflect on each research effort to recover insights which respond to the questions above.

The remainder of this dissertation is structured as follows:

- In the next chapter, I distill the discourse on movement and embodiment in HCI/IxD, landing on a vocabulary of five concepts at its crux.
- Chapters 3–7 present a selection of five peer-reviewed academic journal and conference papers I have co-authored during my PhD studies. Each paper is prefaced by an introductory note with reflections that are founded on the aforementioned vocabulary.
- The final chapter presents a discussion which synthesizes the aforementioned analyses, and presents conclusions intended to inform future work in both practice and scholarship of HCI/IxD by responding to the above questions.

In sum, based on a portfolio of five research projects, this thesis contributes a critique on and implications for the trajectories of technologies and discourse aimed at enriching the physicality of HCI.

Theoretical Foundations

THE ONLY WAY TO EXPERIENCE AN EXPERIENCE IS TO EXPERIENCE IT.

Quote attributed to IDEO co-founder Bill Moggridge (1965–2012),
who is credited for coining the term "interaction design"

Over the last two decades, scholars in HCI/IxD have produced a wealth of discourse on how movement and embodied information figures in understanding and designing interactive computer systems. As with the trends that influence the intellectual basis for the field at large, the growth of interest and discourse on these topics has followed technological developments. It was in the 1990s, for example, that digital cameras became a consumer commodity, and technologies like optical motion capture, which allow for relatively unintrusive sensing of human movement, achieved widespread adoption.[9]

At the turn of the 21st century, reprogrammable microcontrollers became available on the market:[10] the central technology for systems like Arduino[11] which significantly lowered the barrier of entry into sensor-based "physical computing" for artists, designers, and hobbyists. Arguably, reprogrammable microcontrollers gave birth to a whole ecosystem of business and culture: publications such as *Make:* magazine and retailers like Sparkfun and Adafruit[12] were founded in this era to cater to the new population of hobbyists and designers, for whom electronics, sensors, and algorithms became a design material like cloth, wood, or silver.[13] Furthermore, with the second decade of the 21st century, smartphones and other kinds of "mobile devices"—with a wealth of capabilities for sensing, interaction, and connectivity—found their way into the lives of billions. With the availability of these new design materials, the power to build computer systems that sense and act on the physical world was put into the hands of practically everyone. In turn, various visions, theories, and methods were put forward by HCI/IxD scholars to scaffold the utilization of the physical world as a design material for digital artifacts.

By this time, a body of literature encompassing psychology, neuroscience, and philosophy had already developed around concepts like embodied cognition and ecological perception; contrasting with cognitivist and Cartesian-dualist schools of thought.[14] This knowledge

[9] I refer the interested reader to Menache (2011) and Kitagawa and Windsor (2008) for a more comprehensive history of optical motion capture technology, including details on 1980s research efforts and the bumpy road to commoditization in the 1990s.

[10] Dunn, D. (2001). Microchip offering flash at OTP prices. *EE Times*

[11] Kushner, D. (2011). The Making of Arduino. *IEEE spectrum*, 26

[12] Weinberger, M. (2015). How one woman turned her passion for tinkering into a $33 million business – without a dime of funding. *Business Insider*

[13] See Baytaş et al. (2018) for an extended discussion on how electronics and algorithms figure as design materials.

[14] Damasio, A. R. (1994). *Descartes' Error: Emotion, Reason, and the Human Brain*. Avon Books; and Damasio, A. R. (1999). *The feeling of what happens: body and emotion in the making of consciousness*. Harcourt Brace

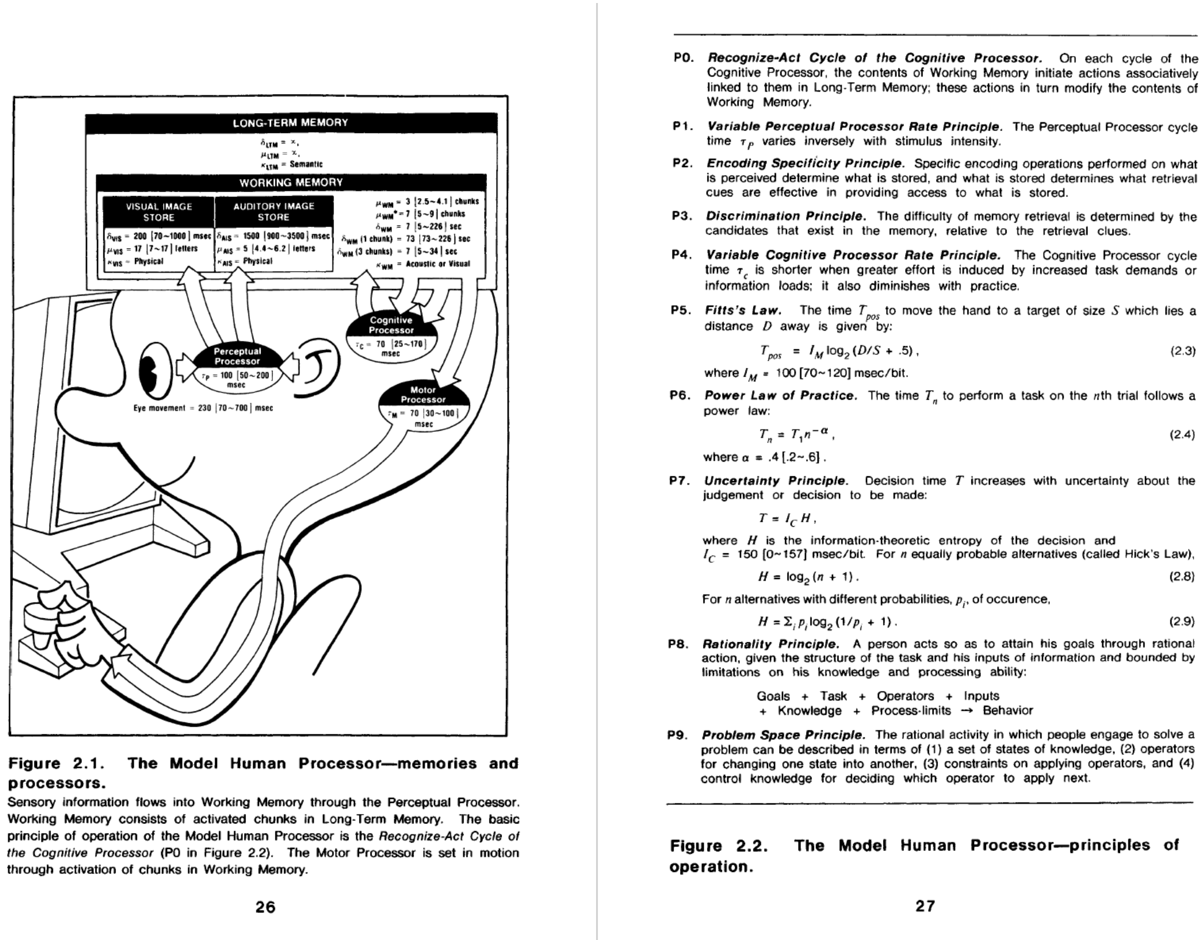

Figure 2.1. The Model Human Processor—memories and processors.
Sensory information flows into Working Memory through the Perceptual Processor. Working Memory consists of activated chunks in Long-Term Memory. The basic principle of operation of the Model Human Processor is the *Recognize-Act Cycle of the Cognitive Processor* (P0 in Figure 2.2). The Motor Processor is set in motion through activation of chunks in Working Memory.

26

P0. ***Recognize-Act Cycle of the Cognitive Processor.*** On each cycle of the Cognitive Processor, the contents of Working Memory initiate actions associatively linked to them in Long-Term Memory; these actions in turn modify the contents of Working Memory.

P1. ***Variable Perceptual Processor Rate Principle.*** The Perceptual Processor cycle time τ_P varies inversely with stimulus intensity.

P2. ***Encoding Specificity Principle.*** Specific encoding operations performed on what is perceived determine what is stored, and what is stored determines what retrieval cues are effective in providing access to what is stored.

P3. ***Discrimination Principle.*** The difficulty of memory retrieval is determined by the candidates that exist in the memory, relative to the retrieval clues.

P4. ***Variable Cognitive Processor Rate Principle.*** The Cognitive Processor cycle time τ_c is shorter when greater effort is induced by increased task demands or information loads; it also diminishes with practice.

P5. ***Fitts's Law.*** The time T_{pos} to move the hand to a target of size S which lies a distance D away is given by:

$$T_{pos} = I_M \log_2 (D/S + .5), \qquad (2.3)$$

where I_M = 100 [70~120] msec/bit.

P6. ***Power Law of Practice.*** The time T_n to perform a task on the nth trial follows a power law:

$$T_n = T_1 n^{-\alpha}, \qquad (2.4)$$

where α = .4 [.2~.6].

P7. ***Uncertainty Principle.*** Decision time T increases with uncertainty about the judgement or decision to be made:

$$T = I_C H,$$

where H is the information-theoretic entropy of the decision and I_C = 150 [0~157] msec/bit. For n equally probable alternatives (called Hick's Law),

$$H = \log_2 (n + 1). \qquad (2.8)$$

For n alternatives with different probabilities, p_i, of occurence,

$$H = \Sigma_i p_i \log_2 (1/p_i + 1). \qquad (2.9)$$

P8. ***Rationality Principle.*** A person acts so as to attain his goals through rational action, given the structure of the task and his inputs of information and bounded by limitations on his knowledge and processing ability:

Goals + Task + Operators + Inputs
+ Knowledge + Process-limits → Behavior

P9. ***Problem Space Principle.*** The rational activity in which people engage to solve a problem can be described in terms of (1) a set of states of knowledge, (2) operators for changing one state into another, (3) constraints on applying operators, and (4) control knowledge for deciding which operator to apply next.

Figure 2.2. The Model Human Processor—principles of operation.

27

Figure 3: Pages 26 and 27 from *The Psychology of Human-Computer Interaction*, illustrating a mechanistic model of human information processing.

was subsequently imported to product design, notably condensing around the notion of "affordances," famously described by Norman (1988),[15] who in turn was drawing on Gibson,[16] pioneer of ecological psychology.

Historically, the task of informing the design of computers for human use was first taken up with positivist and cognitivist commitments:[17] the theories that informed early HCI are very much based on analogies between how humans and computers process information, and early methodology was characterized by an affinity for controlled experimentation and formal modeling, often exposed through the lens of psychology (see Figure 3). In turn, the field of computing in the 21st century developed on such technological and intellectual trajectories that the commitments and methodologies of "first wave"[18] or "classical"[19] HCI had to be reconsidered. The first wave of HCI dealt with "a confined problem space with a clear focus that adopted a small set

[15] Norman, D. A. (1988). *The Psychology of Everyday Things*. Basic Books

[16] Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Houghton Mifflin; and Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Houghton Mifflin

[17] Duarte, E. F. and Baranauskas, M. C. C. (2016). Revisiting the Three HCI Waves: A Preliminary Discussion on Philosophy of Science and Research Paradigms. In *Proc. IHC '16*. ACM

[18] Bødker, S. (2006). When Second Wave HCI Meets Third Wave Challenges. In *Proc. NordiCHI '06*. ACM; and Bødker, S. (2015). Third-wave HCI, 10 Years Later—participation and Sharing. *interactions*, 22(5):24–31

[19] Rogers, Y. (2012). HCI Theory: Classical, Modern, and Contemporary. *Synthesis Lectures on Human-Centered Informatics*, 5(2):1–129

of methods to tackle it — that of designing computer systems to make them more easy and efficient to use by a single user."[20] Its second wave followed the advent of networking: by the end of the 20th century, computers were everywhere, and interconnected via the Internet, becoming centerpieces in collaborative work and social life. In synchrony, HCI scholarship expanded by importing organizational, social, distributed and ecological views in psychology; along with knowledge from sociology and anthropology. Finally, as mobile computing, microcontrollers, and a host of new enablers for "ubiquitous"[21] computing became commodities, "contemporary"[22] (third wave) HCI scholarship turned to introspection,[23] philosophy,[24] and art.[25] Much of the literature on movement and embodiment in HCI follows from this contemporary stream of discourse, where the subjective—experiences, values, and meaning—has come into focus.

[20] Rogers, Y. (2012). HCI Theory: Classical, Modern, and Contemporary. *Synthesis Lectures on Human-Centered Informatics*, 5(2):1–129

[21] Weiser, M. (1993). Ubiquitous computing. *Computer*, (10):71–72

[22] Rogers, Y. (2012). HCI Theory: Classical, Modern, and Contemporary. *Synthesis Lectures on Human-Centered Informatics*, 5(2):1–129

[23] Höök, K., Jonsson, M. P., Ståhl, A., and Mercurio, J. (2016). Somaesthetic appreciation design. In *Proc. CHI '16*. ACM

[24] Dourish, P. (2001). *Where the action is: the foundations of embodied interaction*. MIT press

[25] Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., and Wensveen, S. (2011b). Showroom: Research Meets Design and Art. In *Design Research through Practice: From the Lab, Field, and Showroom*, chapter 6, pages 89–108. Elsevier

An Aside on "Embodiment"

"Embodiment" is not a word that is used often in daily conversation. In common language, *to embody* means to give physical form, to represent, express, and make concrete. In academic language, e.g. in psychology and philosophy, *embodiment* can have connotations having to do with the nature of perception and cognition: *embodied* phenomena are often those experienced on a primal, visceral, and reflexive—rather than deliberative—level. A full linguistic analysis of the term, unfortunately, is beyond the scope of this thesis; though the related literature is acknowledged below. However, as it is a crucial concept for the thesis, I must attempt to briefly define what I mean by "embodiment."

Rather ironically—considering how it connotes the primacy and essentiality of the physical—in my view the best way to describe what *embodiment* means is to start from a physics-inspired viewpoint, assuming an information-theoretical cosmology: that the entire universe consists of, and only of, information; that anything different from nothingness or empty space can be characterized simply as *information*. This then allows us to describe and object, or any *thing* really, in terms of its information content; and our interactions with things as perception and manipulation of information through various *media* or modalities. Thus we can get to the idea of *embodied information*.

Certain aspects of any thing, i.e. certain portions of its information content, can be translated and expressed through other things. For example: if I have an apple, about which I wish to inform you, the reader, I would have many options. I can describe, in as much detail as I wish, various properties of this apple in prose. I can make a drawing, painting, or photograph of the apple, and show it to you. I can compose a song about the apple, and sing it to you. But whatever I do, there will always be some qualities of the apple, some *information* about it, which I will never be able to translate into a medium other than the apple itself—certainly not *efficiently*.

Realistically, I cannot argue that it can ever be possible to convey *all* of the information about a thing through another medium. By this I mean: to the extent that, upon consuming this information, the receiving party would be able to fully *experience* every aspect of the thing, in a way that would be indistinguishable from a direct experience of the thing itself. I can write, for example, entire volumes about the aforementioned apple, but never capture the actual color, taste, weight, or scent. (That is to say, the only way to properly experience the apple is to *experience* it.) However, as a thought experiment, we can suppose such a comprehensive translation of information between media to be theoretically possible: let's say that I could write a book that would convey the full experience of the apple. In this case, the physical "information content" of this book would end up being of larger quantity than its source! The reason for this is simply that the resulting book would comprise the information that describes the apple, along with the information that pertains to its physical substance. We can thus say that there is essential information about the apple, or any thing, that cannot be *compressed* into other media. To perceive information that is *embodied* in a thing requires the thing itself.

Embodied information is that which exists uniquely in a thing itself. Conversely, *embodied interaction*, is simply the perception and manipulation of embodied information.

Key Texts and Vocabulary

The central vision that underlies my work—the idea of using the diverse physical capacities of the world and the human body expansively in interacting with computers—is not new. At the turn of the 21st century, the same challenge was addressed in HCI/IxD scholarship as exemplified by two seminal texts that provided the intellectual basis for a significant volume of subsequent work.

In 1997, Hiroshi Ishii and Brygg Ullmer, recognizing that graphical user interfaces "fall short of embracing the richness of human senses and skills people have developed through a lifetime of interaction with the physical world," proposed a vision for "tangible bits" which motivated a whole genre of HCI/IxD research.[26] The essence of this vision is that embodied cognition can be supported and leveraged in HCI by a multitude of technologies including computer vision, projection mapping, robotics, and augmented reality. In the text, a multitude of inventions by the authors and their colleagues that are described, which illustrate how this might ensue.

In 2001, Paul Dourish published his treatise on "embodied interaction,"[27] seeking to reconcile the "tangible interaction" concept with second-wave HCI[28] through phenomenology—a tradition in philosophy that focuses on the subjective experience as the foundation for ontology and epistemology, i.e. "truth" (p. 103). Unlike Ishii's work on tangible computing, Dourish's approach has its limitations in terms of providing actionable directions for design and engineering. However, his monograph was instrumental in integrating philosophy—the works of Husserl, Heidegger, Wittgenstein, and Merleau-Ponty, in particular—into HCI scholarship.

Ishii's engineering vision and Dourish's philosophy have defined the basis for how movement and embodiment have been treated in subsequent HCI/IxD research.

In the years that followed, the quality and availability of the enabling technologies for embodied interaction rose quickly. Today, for example, augmented reality headsets, components and prototyping tools for sensor/microcontroller systems, and depth cameras that can "see" and localize human body parts are all available as consumer commodities. Simultaneously, a number of theories, frameworks, principles, and guidelines with generative and evaluative potential were developed in academic literature (based on the aforementioned ideas that originate in philosophy, psychology, and neuroscience); so that these technologies can be utilized for novel designs in a sophisticated manner. In this discourse, the central idea is that *to understand, utilize, and serve the human body is imperative for good IxD*. The research projects presented in this thesis have followed from this line of thinking.

[26] Ishii, H. and Ullmer, B. (1997). Tangible bits: Towards seamless interfaces between people, bits and atoms. In *Proc. CHI '97*. ACM

[27] Dourish, P. (2001). *Where the action is: the foundations of embodied interaction*. MIT press

[28] Dourish uses the term "social computing" to refer to the scholarly tradition that I described above as the second wave of HCI.

I must note here that, in addition to the exemplars covered here, the subject of embodiment is taken up in an objectively vast amount of scholarly literature that is diverse in terms of how the concept is understood and utilized. For example, Marshall and Hornecker (2013) treat the phenomenological and psychological perspectives on embodiment as distinct lines of thinking;[29] while the interpretation I present here frames the phenomenological discussion as an evolution of how embodied cognition figures in HCI. Addressing a different side of the issue, Hornecker et al. (2017) elaborate on how embodiment may relate to how preferences on the source, focus, and communication of scholarly knowledge are conceptualized in HCI.[30] Furthermore, there are sources which I have not fully integrated into the central argumentation in this thesis, but nevertheless deserve credit. Any discussion on embodiment within HCI, for example, would be incomplete without acknowledging Fällman's (2003) thesis[31] that deftly synthesizes the discourse on embodiment into a program in constructive design research.[32] And finally, credit must be given to Winograd and Flores who have introduced the ideas of Heidegger to HCI literature as early as 1986.[33] All of this, of course, builds on a tremendous literature in neuroscience, philosophy, and social sciences (mainly psychology), doing justice to which would warrant a whole new research project.

[29] Marshall, P. and Hornecker, E. (2013). Theories of Embodiment in HCI. In Jewitt, C., Price, S., and Brown, B., editors, *The SAGE Handbook of Digital Technology Research*, pages 144–158. SAGE

[30] Hornecker, E., Marshall, P., and Hurtienne, J. (2017). Locating theories of embodiment along three axes: 1st - 3d person, body-context, practice-cognition. In *Proc. CHI '17 Workshop on Soma-Based Design Theory*

[31] Fällman, D. (2003). *In Romance with the Materials of Mobile Interaction: A Phenomenological Approach to the Design of Mobile Information Technology*. PhD thesis, Umeå University

[32] Fällman's argumentation has many parallels with my own, but maintains a strong focus on "mobile" computing.

[33] Winograd, T. and Flores, F. (1986). *Understanding computers and cognition: A new foundation for design.* Intellect Books

To illustrate the aforementioned theoretical contributions on the significance of movement and embodiment matter in HCI and how this figures in practice, I have selected five more recent exemplary texts. In lieu of repeating what is already said in these texts, below, I have opted to summarize and annotate their main ideas in tabulated form.

Following these summaries, I present a set of five notions that distills the commonalities across the ideas in the selected texts, and bears the imprint of the literature summarized above. In tandem with the physics-inspired description which I put forward earlier, this set of five concepts serves to define the meaning of "embodiment" in the context of this thesis; and provides a vocabulary for the subsequent analysis of the compiled research projects.

The selected texts are as follows:

Table 1: Klemmer et al.'s (2006) themes and concepts—synthesized from literature in psychology, sociology, and philosophy—for interaction design that foregrounds the human body.[34]

[34] Klemmer, S. R., Hartmann, B., and Takayama, L. (2006). How Bodies Matter: Five Themes for Interaction Design. In *Proc. DIS '06*. ACM

Table 2: Hummels et al.'s (2007) "guiding principles" for *movement-based interaction*.[35] The authors postulate that first-hand engagement and experience with movement is essential for designing with it, and appropriately, their principles are derived from their own portfolio of research on the topic.

[35] Hummels, C., Overbeeke, K. C., and Klooster, S. (2007). Move to get moved: A search for methods, tools and knowledge to design for expressive and rich movement-based interaction. *Personal Ubiquitous Comput.*, 11(8):677–690

Table 3: Fogtmann et al.'s (2008) two-dimensional conceptual framework for *kinesthetic interaction*, comprising theoretically derived design parameters and themes extracted from a literature survey.[36] The intersections of the parameters and themes (i.e. a "cross" between them) is meant to have both generative and evaluative potential.

[36] Fogtmann, M. H., Fritsch, J., and Kortbek, K. J. (2008). Kinesthetic interaction: Revealing the bodily potential in interaction design. In *Proc. OZCHI '08*. ACM

Table 4: Jacob et al.'s (2008) themes and concepts which make up a framework for *Reality-Based Interaction*.[37] The theory is derived from eclectic sources (i.e. literature, interviews, and a workshop), but thoroughly justified via case studies and an explication of its limitations.

[37] Jacob, R. J., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Solovey, E. T., and Zigelbaum, J. (2008). Reality-based interaction: A framework for post-wimp interfaces. In *Proc. CHI '08*. ACM

Table 5: Höök et al.'s (2016) "qualities" for *somaesthetic appreciation design*.[38] In line with Hummels et al., the authors foreground first-person experience in designing with and for the body, and base their theory largely on their own research portfolio, as well as justifying it by application to design exemplars.

[38] Höök, K., Jonsson, M. P., Ståhl, A., and Mercurio, J. (2016). Somaesthetic appreciation design. In *Proc. CHI '16*. ACM

Themes and Concepts	Explanatory Notes
Thinking through Doing	*Physical interaction with the world is essential for thinking and learning.*
Learning through Doing	*Engagement with the physical world facilitates cognitive development.*
The Role of Gesture	*Gestures precede language in human communication, historically and developmentally.*
Epistemic Action	*Manipulating the physical facilitates sense-making...*
vs. Pragmatic Action	*...which is distinct from goal-driven manipulation.*
Thinking through Prototyping	*Physical creation facilitates invention...*
Reflective Practice	*...as materials "talk back" to the designer.*
On Representation	*Solving a problem often hinges on representing it well:...*
Tangibility	*...analogies with physical world can be a viable representation strategy for novel UIs...*
Natural Mappings	*...as well as analogies with human communication and cultural constructs.*
Performance	*Bodily movement and proprioception are powerful capabilities to leverage for IxD.*
Action-centered Skills	*Expert knowledge is often tacit—"we know more than we can tell" (Polanyi, 1967).*
Hands	*Hands are extremely powerful manipulation and sensing instruments.*
Motor Memory	*Proprioception and kinesthetic memory can be leveraged for "skillful" IxD.*
Reflective Reasoning Is Too Slow	*Physical reflexes and "kinesthetic recall" are much more efficient in many cases...*
Experiential vs. Reflective Cognition	*...compared to deliberate reasoning.*
Visibility	*Visibility makes group work efficient.*
The Social Life of Physical Artifacts	*Shared physical artifacts are essential for working in groups.*
Situated Learning	*Visibility of work is essential for learning by observation, e.g. apprenticeship.*
Visibility Facilitates Coordination	*Visible physical work provides constant status updates to co-workers.*
That's What Performance is About	*Performance = "visibility of creative production"*
Verified Voting	*The only indisputable evidence is the physical (e.g. paper votes).*
Risk	*There is no "undo" in the physical world.*
Physical Action is Characterized by Risk	*Values like trust, commitment, responsibility, and focus can be brought into IxD via risk.*
Trust and Commitment	*Face-to-face interaction should be supported for efficacious group work...*
Distance Matters	*...since proximity and interpersonal engagement matters.*
Personal Responsibility	*The visibility of the decision-maker can incrase responsibility and decision quality.*
Attention	*Risk inspires focus.*
Thick Practice	*"There is so much benefit in the physical world, great care must be taken before replacing it"*
Interfaces that are the real world	*Augmenting existing interactions with new outcomes can be an IxD strategy.*

Table 1: Klemmer et al.'s (2006) themes and concepts for interaction design, synthesized from theories of embodiment in psychology, sociology, and philosophy; annotated in italics with explanatory notes, and added items to capture sub-concepts and hierarchy in detail.

Meaning through Interaction
"...we perceive the world in terms of what we can do with it."
"...the world is inherently meaningful for our body, and by moving we can get access to that meaning."

Richness of Interaction
"Electronic consumer products are tangible to start with, so one should not focus on the tangibility of the interaction but on the richness of the interaction."

Design by Moving
"...we need new methods and techniques to design these interactions and accompanying products."

Support for Movement
"Designers need tools that help them to explore and visualise interactions [...]."
"These tools should exploit the expressive rich repertoire of designers' movement to incite the expressive rich repertoire of the users' movements and even the product's movements."

Research by Doing
"[Research through design] enhances reflection-in-action and on-action again for designers and users, which not only constitutes design knowledge but also helps to generate new hypotheses."

Educate through and for Movement
"...we also have to educate our future designers. We have to provide knowledge and offer them methods, tools and techniques (including their own bodies) to facilitate the design process."

Design for Diversity
"Because we all have our own physical, emotional and rational characteristics, our own history in life and our own needs, our preferred movements will differ, and consequently we prefer different possibilities for action."

Table 2: Hummels et al.'s (2007) "guiding principles" for *movement-based interaction*; explained through quotes from the original text.

Design Parameters		Design Themes
Engagement *Bodily motion is to be leveraged for engagement with the apploication.*		
Sociality *Mind the social context, with co-users or bystanders.*		**Kinesthetic Development** *The goal is to acquire/develop bodily skills.*
Movability *Mind and leverage free vs. restricted movement.*		
Explicit Motivation *Tell the user what to do, i.e. pose expectations and restrictions.*	×	**Kinesthetic Means** *The goal is not physical, but abstract; e.g. learning or playfulness.*
Implicit Motivation *Provide open, exploratory interaction possibilities.*		
Expressive Meaning *Make bodily engagement and system output congruent.*		**Kinesthetic Disorder** *Extra-ordinary sensations and movements are provided/expected.*
Kinesthetic Empathy *Leverage interactions with the environment and other people therein.*		

Table 3: Fogtmann et al.'s (2008) conceptual framework for *kinesthetic interaction*; annotated in italics with design directives and concise definitions.

Naïve Physics *Gravity, mass, friction, rigidity, velocity, springiness, inertia, object persistence...*
Body Awareness and Skills *Proprioception* *Range of Motion* *Movement Coordination* *Two-handed and whole-body interaction* *Walking*
Environment Awareness and Skills *Orientation, navigation* *Horizon* *Atmospthetic color, fog, lighting, shadow* *Distance and size relationships* *Grasping, positioning*
Social Awareness and Skills *Verbal and nonverbal communication* *Exchanging objects*

Table 4: Themes and concepts proposed by Jacob et al. (2008) to drive their *Reality-Based Interaction* design framework; annotated in italics with examples to capture the meaning of each item, as well as how it can be implemented in IxD.

Subtle guidance - directing attention inwards "...we perceive the world in terms of what we can do with it." "...the world is inherently meaningful for our body, and by moving we can get access to that meaning."
Making space - temporal, interactive and spatial places for reflection "Electronic consumer products are tangible to start with, so one should not focus on the tangibility of the interaction but on the richness of the interaction."
Intimate correspondence - feedback and interactions that follow the rhythm of the body "...we need new methods and techniques to design these interactions and accompanying products."
Articulating experience – providing means to articulate the experienced bodily sensations "Designers need tools that help them to explore and visualise interactions [...]." "These tools should exploit the expressive rich repertoire of designers' movement to incite the expressive rich repertoire of the users' movements and even the product's movements."

Table 5: Höök et al.'s (2016) "qualities" for *somaesthetic appreciation design*.

The essence of the concepts that appear across these selected texts (and those that they build on) can be distilled into the following five notions:

1. **Integration.**
Movement and embodiment are two sides of the same coin. Embodied perception and cognition takes place through human movement of the body, and the senses. Changing sensory perspectives through movement is how we make sense of embodied information (see also: Sousanis 2015). Likewise, movements of the human and those of objects in the environment, as well as the embodied experience and the tangibility of the environment, are two aspects of the same. The agent and the environment exist in relation to each other. Without one, the other does not make sense. *Embodiment* is a concept that captures the physicality of experience and environment; and physicality consists of movement. Coming back to our physics-inspired information-theoretical cosmology: movement, on every scale (e.g. from galactic to subatomic), is the embodiment of information. What does not move, does not exist. Movement *is* embodiment.
2. **Primacy.**
Embodied perception and cognition precedes language, logic, and deliberation—in both historical and individual trajectories for the development of human communication. In HCI/IxD: it makes sense to design for embodied perception and action first; but also to appreciate the sophistication in language, symbols, and didactics. After all, language developed for (a) reason.
3. **Subjectivity.**
Embodied information, by definition, cannot be translated and transmitted through other media, e.g. language and images; it only makes sense from the first-person perspective. In HCI/IxD: making sense of embodied interaction requires the scholar or designer to be fully immersed in the situations and artifacts at hand. This challenges the epistemology of first- and second-wave HCI, and justifies its contemporary formulation.
4. **Intersubjectivity.**
The limitation of embodied interaction is its strengths at the same time: while embodied information cannot be translated and transferred, it will be jointly understood when experienced together. This joint understanding is unique to embodied interaction, and cannot be conveyed otherwise. In HCI/IxD: this motivates tangible computing; along with a space for invention where intersubjectivity might be captured in technology.
5. **Materiality.**
The nature of digital materials is at odds with the philosophy of embodied interaction. While the digital comes in infinite forms, embodiment hinges on uniqueness of form. In HCI/IxD: this poses a dilemma. Should we all abandon lights and circuits, to take up watchmaking or carpentry (see: Baytaş et al. 2018)? Or should we, again, take this as a push for invention?

These notions are meant to serve as a *vocabulary* to facilitate analyses of the research projects I have conducted, which center around embodied interaction with computers. In what follows, I present five research papers that are each prefaced with reflections that use this vocabulary. These reflections aim to articulate the potentials and shortcomings of the technologies and methodologies featured in each research project, and collectively suggest how both theory and technology may evolve to better serve the vision of rich physicality in embodied HCI.

The Perception of Live-sequenced Electronic Music

...IF TECHNOLOGY IS TO PROVIDE AN ADVANTAGE, THE CORRESPONDENCE TO THE REAL WORLD MUST BREAK DOWN AT SOME POINT.

Grudin (1989)

The evolution of musical style is intimately tied to technology; to the extent that technological determinism and audience-centered pragmatism, more than intimate creativity, seems to explain a great deal about why music sounds the way it does in each era.[39] Within the current technological and social context, techno is a musical genre that is archetypally situated. The sound of today's techno would be practically impossible to even imagine in a previous age: it relies on modern software for its production, and modern speaker systems with extended frequency ranges for its reproduction. Techno's technological imprint, however, has an ironic corollary: On one hand, the hallmark of *good* techno, in my opinion, is meaning to be experienced with the whole body, not with the ears alone. Good techno is made to be played in a club. It harnesses the extended low frequency ranges of modern club speakers, which can produce legible vibrations that are to be *felt*, rather than heard. On the other hand, the instruments used to produce techno are almost entirely incongruent in terms of embodied interaction. The experience of making live techno music, from both first-person and audience perspectives, is more akin to programming than playing music. This is why I prefer to say that live techno is *sequenced*, rather than *played* by the performer.

[39] An expansive discussion on this topic is, unfortunately, not possible within the scope of this dissertation; but I can refer the interested reader to sources that have informed my point of view: Byrne (2012), Katz (2010), and Ross (2008).

The experience of live techno music is, in some ways, the complete opposite of more traditional musical performances. Techno music is about the bodies of the audience,[40] while the body and movements of the performer are often an afterthought. The audience is not expected to watch the performance. The audience is not there as spectators; as they move, they are part of the performance. The audience, rather than the performer, embodies the physicality of techno. From an HCI/IxD perspective, this is an opportune space. Here we find many open questions, and multiple dimensions along which both the performer's and the audience's experiences can be enhanced (or otherwise experimented with). The project at hand, in fact, began with such an aim.

[40] Garcia, L.-M. (2015). Beats, flesh, and grain: sonic tactility and affect in electronic dance music. *Sound Studies*, 1(1):59–76

At the time, I was leading a second life as a musician. My musical life, in turn, was further split in two. I was playing bass guitar in a rock band, which involved copious physical labor both on and off stage, and facing relatively small audiences who rarely had any kinetic energy. I was also performing as a DJ, for which the labor is of an entirely different character. Being a DJ, to me, was about preparing by sitting in a chair, curating tracks on a computer while sipping coffee; and performing by loafing behind the decks, pressing a few buttons while sipping a drink. The energy of the (significantly larger) audiences, however, was electrifying. I wanted the best of both worlds: I wanted the energetic audience, and the embodied interaction.

To address the challenge, I turned to HCI scholarship, starting with the basics, and perhaps the most fundamental question: Is there any value in watching a performer create techno music with today's human-computer interfaces, and how do we characterize that value? In other words, is there even a point to having a human performer on stage at all? And if there is, how does it compare to a more traditional, instrument-playing performance?

Reflections and Insights

The method I used to explore the above questions was a lab experiment, where the procedure was adapted from a well-cited paper on music perception, published in a prominent journal for cognitive sciences. The principal finding was that spectators reflexively pay attention to, and seek meaning in, the interactions between the performer and his instruments. In a way, through laborious empirical work, in a musical context, we had corroborated what scholars have theorized about the *primacy*, *intersubjectivity* and *materiality* of embodiment in HCI. That is to say, our results point to a high level of attention and engagement on part of the audience, directed at the musical devices and the performer's interactions with them; even while they do not fully comprehend what the devices really are, what sounds are made by what device, and what gestures/interactions are linked to what sonic events. Furthermore, while the visual and sonic experiences seem to have some commonality (evident in a visual inspection of the resulting graphs), the portions of the performance where the visual and sonic perceptions of tension correlate significantly are mostly aligned with bodily gestures that have immediate, direct bearing on the musical result. In simpler terms: while there is some value indeed in the spectacle of a performer *sequencing* music rather than playing an instrument, the performance becomes more exciting when gesture and sound are immediately congruent.

In addition to the findings resulting from the study itself, conducting this study was a significant learning experience that influenced how I viewed and executed my subsequent research. While the format and size of the paper did not allow for extensive discussion of the methodological limitations we encountered, the fact is that this particular experimental approach turned out to be limited in terms of informing design. While the impetus behind this experiment was to inform the design of novel interfaces for creating electronic music, when we were done executing the study and analyzing the data, we were left with very few significant insights that could drive any concrete design work. It is only now, through the lens of contemporary HCI epistemology and methodology that I was able to digest in the years that followed, I can appreciate the limitations associated with the idea of studying an embodied phenomenon by presenting videos on a computer screen. The study stands as an academic exercise on how an approach from the psychology of music perception can be applied to investigate an HCI phenomenon; but in terms of my personal research trajectory it marks the moment when I came to grips with the commitments of "classical" or "first-wave" HCI approaches, their limits, and what lies beyond them.

Baytaş, M.A., Göksun, T., & Özcan, O. (2016). The Perception of Live-sequenced Electronic Music via Hearing and Sight. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (NIME 2016).

HCI research contribution type(s): Empirical study.

Authors' contributions: I reviewed the literature, designed the study, build the apparatus and organized logistics, recruited participants, ran the study, analyzed the data, produced visualizations and diagrams, and wrote the paper. Co-authors supervised and validated study design, data analysis, and argumentation; and edited the paper.

The Perception of Live-sequenced Electronic Music via Hearing and Sight
can be downloaded at:
nime.org/proceedings/2016/nime2016_paper0040.pdf

Drama-based Education for Designers of Gestural UIs

...THE BODY IS SEEN AS AN "INPUT DEVICE"...
... AS AN INSTRUMENT THROUGH WHICH WE MAKE MIND RULE OVER MATTER.

Höök (2018)

Earlier in the thesis, I attempted to provide the reader with a scholarly perspective on movement and embodiment in HCI/IxD. While this perspective certainly has entertainment value for the reader interested in scholarly discourse, as well as creative potential for the erudite designer, it has its limitations in terms of audiences it can reach. Even as a programmer with a decade of experience, I have only very recently started being able to utilize (and, when needed, critique) this perspective in my work, in a way that does justice to it. Making this knowledge accessible to broader audiences is a challenge.

This paper reports on a novel drama-based education approach for interaction designers which would facilitate their utilization of human movement as a design material. This effort was situated in a broader research program that was motivated by rapid advances and popularization of mid-air gesture-sensing technologies, and aimed to lower the barriers of entry for designers, artists, and students into utilizing these new design materials. We attacked the problem from many fronts. One was to create new tools for this purpose: we designed, built, and released an open-source graphical gesture authoring interface to enable those without engineering prowess.[41] Another front was education. At the time, my colleagues were working with design students who had little experience in building software, but had the potential to contribute to software design through their creative skills. The challenge was taken up to introduce these students to the world of gestural interfaces and help them leverage their existing skills in this new domain, through a short training course. In a way, the goal was to create an entry point for hands-on creatives into both the technology and philosophy of gestural HCI.

[41] Baytaş, M. A. (2014). End-user authoring of mid-air gestural interactions. Master's thesis, Koç University; Baytaş, M. A., Yemez, Y., and Özcan, O. (2014a). Hotspotizer: End-user authoring of mid-air gestural interactions. In *Proc. NordiCHI '14*. ACM; and Baytaş, M. A., Yemez, Y., and Özcan, O. (2014b). User interface paradigms for visually authoring mid-air gestures: A survey and a provocation. In *Proc. EGMI '14*. CEUR

Reflections and Insights

The way that this paper reports on our work foregrounds design and creative aspects, and speaks to contemporary HCI scholarship (as well as the conventions of the publication where it appeared). On the other hand, there are aspects to this project that resonate with second-wave HCI. For example, many of the exercises that comprised the training program reported here highlighted and motivated considerations related to the social qualities of gestural HCI. The way that human-to-machine interactions were articulated and analyzed in practice, during the course, was often founded on conversational analogy. In terms of scholarly ideas on movement and embodiment in HCI, the focus was strongly on supporting designers in cultivating an appreciation for using the subjective self in gestural HCI design, and minding the intersubjective nature of these interactions at the same time. These notions, though not explicated in the paper, underpinned the project in practice. Conversely, in my opinion, these associations also coincide with a limitation, in that we perhaps layered too much of an abstraction over the technology. While mime and drama techniques indeed bore potential in facilitating ideation and early-stage prototyping, I have observed that they are no substitute for subjectively experiencing the technology itself as a design material.

When it comes to implications at the intersection of technology and discourse, perhaps the most salient learning that I took away from the project at large was this: While the gesture sensing technology that we worked with presented exciting potentials, it lacked the *materiality* that would facilitate desirable user experiences. Here I do not mean to refer to the fact that mid-air gesturing does not fully engage the tactile sense, which we usually associate with materiality; but I refer to the lack of a distinct set of obvious constraints and affordances for making and engaging with this material. This insight, which I came to appreciate in the course of this project, later led to the articulations on materiality that lay at the foundation of some later work.[42]

[42] Baytaş, M. A., Coşkun, A., Yantaç, A. E., and Fjeld, M. (2018). Towards materials for computational heirlooms: Blockchains and wristwatches. In *Proc. DIS '18*. ACM

Ünlüer, A. A., Baytaş, M. A., Buruk, O. T., Cemalcilar, Z., Yemez, Y., and Özcan, O. (2017). The Effectiveness of Mime-Based Creative Drama Education for Exploring Gesture-Based User Interfaces. *International Journal of Art & Design Education*, 37(3), 353-366.

Research contribution type(s): Empirical study, methodology.

Authors' contributions: I made significant contributions to literature review, data analysis, argumentation, and writing the paper; and contributed to designing and running the empirical work. The first author made the majority of contributions in designing, running, and documenting the empirical work. The third author contributed to literature review, data analysis, argumentation, and writing. The other co-authors supervised and validated empirical design, data analysis, and argumentation; and edited the paper. While I did not initiate this project and lead the empirical work, the inclusion of this paper as part of my doctoral thesis is justified in that I have contributed the majority of work towards realizing this publication (which ensued after the empirical work was completed), and I have made significant contributions that are integrated to the larger research program in which this project was situated (see: Baytaş 2014; Baytaş et al. 2014a,b).

The Effectiveness of Mime-Based Creative Drama Education for Exploring Gesture-Based User Interfaces
can be downloaded at:
onlinelibrary.wiley.com/doi/abs/10.1111/jade.12136

LabDesignAR

IF THE COMPUTER IS THE SOLUTION, THEN INFORMATION IS THE PROBLEM.

Dahlbom and Mathiassen (1993)

The idea behind LabDesignAR was simple: take an application that exists on a screen, and break it out into the 3-dimensional world.

Professional motion capture systems can be expensive and complicated. Before setting one up in a new space, it pays off to plan well. What kinds of cameras and lenses should be used? Where should the cameras be placed? What are some architectural features or objects in the room, that might interfere? It pays off to figure out the answers to such questions before you pack up and ship the system.

At a company that makes the systems, there will be experts who can answer such questions quickly. However, there will also be personnel who might not have the same expertise, experts who would like to visualize and validate rather than go with intuition and calculation alone, and customers who would like more evidence that they will get what they need. For these reasons, among others, there are tools for modeling camera setups in virtual environments.

Qualisys' *Lab Designer*[43] was an example for such a tool—a web application where simple 3D models of rooms and cameras can be built to figure out system specifications (see Figure 4). This was the perfect use case for experimenting with augmented reality (AR) and embodied interaction. What if, instead of working with a virtual room on a screen, we could walk into the actual room and model the equipment *in situ*? What is there to be gained from such an invention, and what will be the cost? Will current technology suffice to realize this experience properly?

[43] labdesigner.qualisys.com

Reflections and Insights

I built *LabDesignAR* to explore the issues above, and promptly ran into new ones. While the idea was straightforward and turned out to be viable for the most part, interacting with a collection of multiple holographic objects spread out across a room posed some interesting design challenges. Very quickly, I ran into the technical limits of the hardware I was working with—for example, the headset that I used was not able to render holograms properly at distances I wanted to see (too far) and interact with them (too close). Even when I integrated additional sensors into the setup, gesture recognition capabilities did not add up to a "natural" user interface. (Thus I came to fully appreciate Don Norman's argument on how "natural user interfaces are not natural."[44])

[44] Norman, D. A. (2010). Natural user interfaces are not natural. *Interactions*, 17(3)

The most interesting challenges regarding the system, those which eventually precluded its adoption by personnel at Qualisys, resonated with what scholars had identified already in theories on embodiment on movement in HCI: in moving the rendering from the screen to the headset, I had destroyed the materiality and intersubjectivity of interaction. Salespeople and customers did not find the interactions "natural," and could not huddle together around a model and manipulate it together when it can only be seen by one. Even when two connected headsets are employed, the experience was not the same as interacting with the *same* object together. Though various flavors of AR had been long touted as potential enablers for compelling embodied interaction design, the inability to create a compelling intersubjective experience severely limited its appeal.

In addition to the technical and experience limitations encountered during this project, another issue I had was methodological. How could I even evaluate this artifact, when the people for whom it would make sense were such a small population, and did not show obvious interest in spending time with it to become skilled enough in its use? In the end, the academic result of this project was framed as an artifact contribution and presented as a demonstration. These challenges, however, turned me to the philosophy of contemporary, or third-wave, HCI; in addition to the usage of alternative strategies for validating design concepts, including those that draw on philosophy and art.

Baytaş, M.A., Yantaç, A.E., & Fjeld, M. (2017). LabDesignAR: Configuring Multi-camera Motion Capture Systems in Augmented Reality. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (VRST '17).

Research contribution type(s): Artifact

Authors' contributions: I reviewed the literature; designed, built, and documented the artifact; and wrote the paper. Co-authors supervised and validated the design and argumentation; and edited the paper.

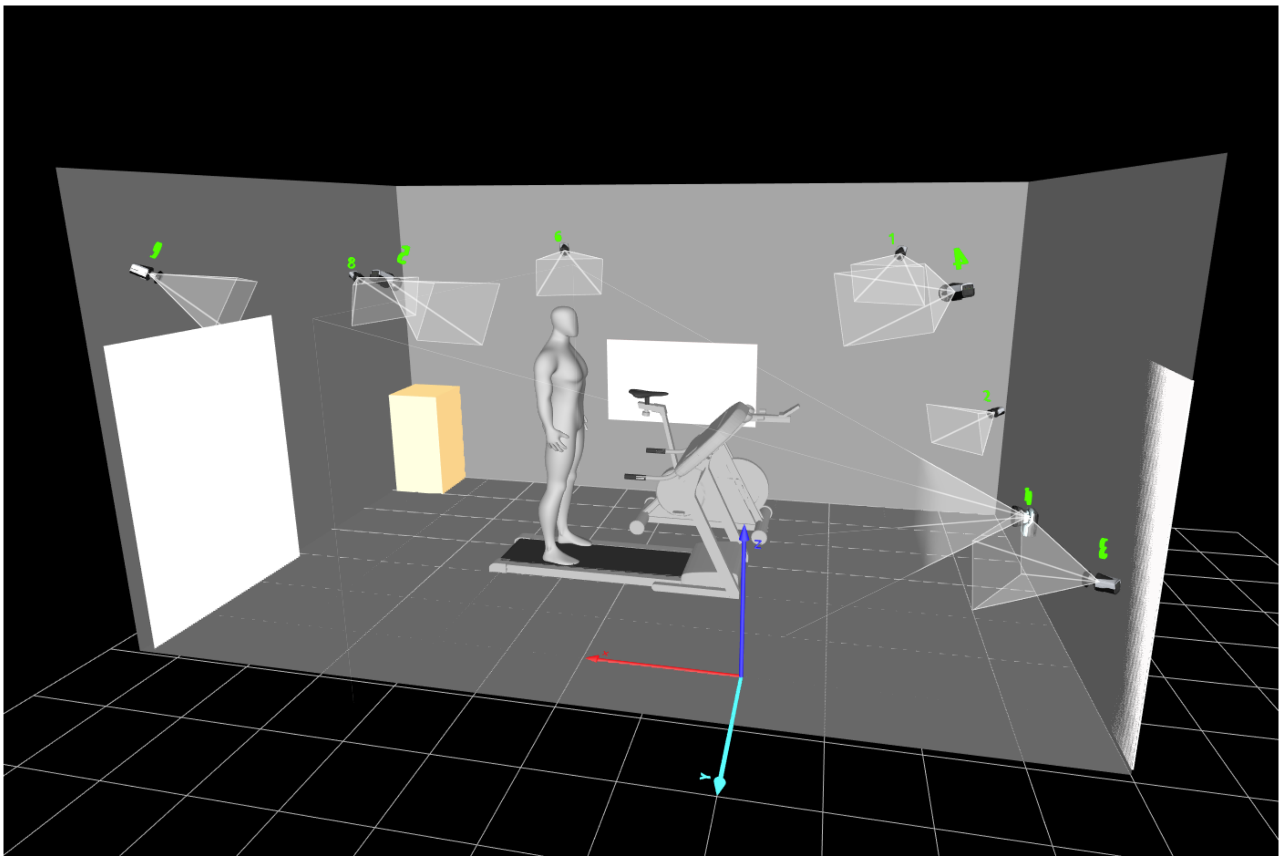

Figure 4: A 3D model created with the Qualisys Lab Designer, to experiment with camera selection and placement for an optical motion capture system.

LabDesignAR: Configuring Multi-camera Motion Capture Systems in Augmented Reality
can be downloaded at:
doi.acm.org/10.1145/3139131.3141778

Computational Heirlooms

WE WERE INSPIRED BY THE AESTHETICS AND RICH AFFORDANCES OF THESE HISTORICAL SCIENTIFIC INSTRUMENTS, MOST OF WHICH HAVE DISAPPEARED FROM SCHOOLS, LABORATORIES, AND DESIGN STUDIOS AND HAVE BEEN REPLACED WITH THE MOST GENERAL OF APPLIANCES: PERSONAL COMPUTERS.

Ishii and Ullmer (1997)

During the course of the five years that elapsed between beginning my doctoral studies and writing this text, I went through eight computers and four smartphones. (The average American consumer reportedly replaces their smartphone before spending 2 years with it. I console myself imagining that faster turnover is common for those in my profession.) Conversely, throughout this time, I have been wearing a mechanical wristwatch manufactured in 1971, practically every day. In fact, I have been wearing it for the last 15 years or so; and before that, my father wore it for years before stowing it away in a drawer for me to discover.

Computers today can have infinite forms, and infinite functions; but fall short of affording this kind of longevity and experience. What would it take to have the kind of user experience that a 50-year old mechanical gadget provides, coupled with the powers of modern computing? Can we design and build computational artifacts today, that are intended to outlast their owners? Can we somehow make computers that, after decades, will be still as functional and valuable (if not more valuable) as on day one?

This project addressed these questions conceptually. I was not the first person to ponder them, and to be driven to investigate. But when we looked into the scholarship that was done before, we were able to synthesize new ideas that culminated in novel research contributions. The present research paper is based on a synthesis of philosophical arguments and empirical findings in previous work, to serve a vision that draws from personal experience. In a previous era, this kind of work would probably not be appreciated as scholarship within computer science. Situated in the contemporary HCI/IxD research tradition, our work was acknowledged with an award for excellence.

Reflections and Insights

The concept covered in the research paper presented here can be on two levels. First, the broader, high-level concept of "computational heirlooms" arises from desiring a particular user experience, in a digital system, that would be innate in many kinds of physical, mechanical devices. Second, a particular manifestation of this concept is proposed, grounded in a real scenario where it is argued to be useful. The conceptual level is motivated by the understanding of materiality as affordances for making, which was triggered by my previous work on gesture sensing[45]. It was in this paper that I was able to properly articulate this interpretation of materiality in interaction design, which also in turn led me to reflect in a more sophisticated fashion on my work in gesture sensing. On the particular level, the design we propose leveraged the primacy and integration of movement and embodiment with regard to human perception and action. Implicitly, these two attributes are leveraged to motivate an interface comprising purely mechanical components in a computational system. The mechanical wristwatch is presented as a superlative example to inform the design of such a device, owing to its ability to communicate sophisticated information on both timekeeping and its own functioning by way of movement. (The fact that these artifacts are powered by movement—either through an internal rotor or via winding—was a happy coincidence that reinforced the metaphor.)

[45] See: our work on training designers of gestural interfaces (Ünlüer et al., 2018) and associated commentary, in a previous chapter.

Finally, with regard to methodology, this research project represents an interesting turn where I considered the research and its reporting in an integrated fashion. Contrary to the more conventional approach, we did not conduct certain studies and write a paper to report on them. Many design research projects hinge on tactical work and the prose comes as an afterthought; as researchers write and submit papers in order to get academic credit for their design work. In contrast, this was a literary project, where we began by drafting and iteratively refining the paper as both means and end in itself. (I later learned that this kind of approach is more common in fields like anthropology, where, for example, the qualities of ethnographic writing and the underlying fieldwork can be equally privileged.) Based on this undertaking, I became more aware of the validity of prose as a way of prototyping and communicating design concepts.

Baytaş, M.A., Coşkun, A., Yantaç, A.E., & Fjeld, M. (2018). Towards Materials for Computational Heirlooms: Blockchains and Wristwatches. In *Proceedings of the 2018 Conference on Designing Interactive Systems* (DIS 2018). [Best Paper Award]

Research contribution type(s): Artifact, theory, survey, opinion.

Authors' contributions: I reviewed the literature, synthesized and developed the concept, and wrote the paper. The second author actively took part in theorizing, argumentation, and concept development. Other co-authors supervised and validated the methodology, concept, and argumentation; and edited the paper.

Towards Materials for Computational Heirlooms: Blockchains and Wristwatches
can be downloaded at:
doi.acm.org/10.1145/3196709.3196778

The Design of Social Drones

…WE DESCRIBE THE EMERGENCE OF AN INTERDISCIPLINARY FIELD OF SCIENTIFIC STUDY. THIS FIELD IS CONCERNED WITH THE SCIENTIFIC STUDY OF INTELLIGENT MACHINES, NOT AS ENGINEERING ARTEFACTS, BUT AS A CLASS OF ACTORS WITH PARTICULAR BEHAVIOURAL PATTERNS AND ECOLOGY.

Rahwan et al. (2019)

In early HCI, contrary to the wording of its founders, the computer is taken a machine. In HCI's second wave, the machine becomes part of the conversation, but it remains a machine, set apart in its own world, isolated from human socialization. In third wave HCI, the machine has infinite forms, to the extent that the reconsideration of the category is warranted.[46] Today, there are those who would argue to consider the computer as an intelligent agent with its own psychology.[47]. The impetus for *design*, then, is to figure out how these agents should *behave*.

The quadcopter drone[48] is an extremely versatile machine already, and a platform for invention too. While today, drones are mostly used as flying sensor packages or means for an out-of-body experience (as in recreational racing), the future we expect will have them in our homes, offices, and streets as companions, servants, and "flying user interfaces."[49] And, for the purposes of this dissertation, the potential of a flying robot in speaking to theories of embodied HCI (as with many other kinds of robots) is obvious.

We took up this topic by focusing on the experience of interacting with the drone, and synthesized the findings across many empirical studies on the topic—all of them conducted within the last decade.

[46] Dunne, A. (2005). *Hertzian Tales*, chapter 2, pages 21–42. MIT Press, 2005 edition edition

[47] Rahwan, I., Cebrian, M., Obradovich, N., Bongard, J., Bonnefon, J.-F., Breazeal, C., Crandall, J. W., Christakis, N. A., Couzin, I. D., Jackson, M. O., Jennings, N. R., Kamar, E., Kloumann, I. M., Larochelle, H., Lazer, D., McElreath, R., Mislove, A., Parkes, D. C., Pentland, A. S., Roberts, M. E., Shariff, A., Tenenbaum, J. B., and Wellman, M. (2019). Machine behaviour. *Nature*, 568(7753):477–486

[48] While currently, for many applications, the quadcopter form factor is optimal; it has drawbacks like unwanted noise and airflow. I find it plausible that other form factors for drones may eventually prevail.

[49] Funk, M. (2018). Human-drone interaction: Let's get ready for flying user interfaces! *Interactions*, 25(3)

Reflections and Insights

The drone is an interesting design material, as it is very physical and tangible, but most often cannot actually be touched or grasped while it is operating. On larger drones, doing so would be dangerous; and even with smaller drones, grabbing one is not a very comfortable experience, and often disrupts the drone's flight. However, what we learn from both experience and studies with drones makes the case for the integration of embodied presence and movement, driven home by the fact that the drone's movements can carry a wealth of information that humans can interpret intuitively or consciously.

Drone technology also represents interesting potentials in terms of how it might advance use cases for technologies like augmented reality and gesture sensing, which have been long touted as enablers of embodied interaction, despite limitations that have not yet been conquered. Loading projectors on a drone, for example, can be a method for projection-based augmented reality that overcomes the problem of unconvincing intersubjectivity that limits headset-based implementations. With gesture sensing, a principal limitation is that the space in which gestures are sensed is confined to the line of sight of the sensors, and communicating the confines to the user comes up as a design challenge. If the sensor was attached to a drone, for example, its position could be changed adaptively, and the problem is obviated.

One of the most interesting design issues with drones and other robots, however, relates to the notion that embodied perception and cognition is primal—the phenomenon of an embodied, articulated machine is processed on an instinctive level, before logic and deliberation come into play. Hence, for example, many studies report that people often interact with drones (as well as other robots) as if they are some kind of animal, like a pet. Humans are quick to assign conscious agency to autonomous robots. In my opinion, this is a very significant topic for design, and fortunately, theoretical frameworks that can inform designers in dealing with these issues are presently developing.[50] Unfortunately, I feel that this comes in as an important weakness in our paper, as we have not dealt with this issue with the sophistication it warrants. I hope to address this limitation in future work.

[50] Rozendaal, M. C., Boon, B., and Kaptelinin, V. (2019). Objects with intent: Designing everyday things as collaborative partners. *ACM Trans. Comput.-Hum. Interact.*, 26(4):26:1–26:33

Baytaş, M.A., Çay, D., Zhang, Y., Obaid, M., Yantaç, A.E., & Fjeld, M. (2019). The Design of Social Drones: A Review of Studies on Autonomous Flyers in Inhabited Environments. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (CHI 2019).

Research contribution type(s): Survey, opinion.

Authors' contributions: I designed the review process, produced around half and edited all of the intermediate documents during the review process, produced the online content, and wrote the paper. The second and third authors contributed to the review and producing intermediate documents. The third author co-designed the review process and argumentation. The final three co-authors supervised and validated the design and argumentation; and edited the paper.

The Design of Social Drones: A Review of Studies on Autonomous Flyers in Inhabited Environments
can be downloaded at:
doi.acm.org/10.1145/3290605.3300480

Discussion and Conclusion

EMPTIED FROM ALL HUMAN MOTION / CONFRONT THE FACELESS WRATH

Strömblad et al. (1994)

Refocus

With this dissertation, I set out to advance a vision of diverse physicality in human computer interaction. Initially I had asked: *How might we enjoy the productivity and amusement afforded by computers, and still experience an abundance of physical experiences while doing so?*

This first-order framing articulates a vision, but a vision—as opposed to a "goal," "aim," or "objective"—might not always be enough to drive action. In my case, a significant issue was that my vision—though it motivated me strongly—represents nothing novel. The themes of *embodied interaction* and *tangible computing* have been canonical topics in my field for very long. However, it struck me that designs which build on such visions have not prevailed on the market for computing artifacts. This mismatch between a prevalent vision in HCI scholarship and the current technological landscape brought the following questions to my attention, which represent a refinement and reframing of the vision:

- How does the discourse on movement and embodiment in HCI literature towards creating diverse physicality in HCI speak to current emerging technologies that are on their way to commodification?
- How can we articulate the potentials and shortcomings of the current technological and theoretical landscape, in order to serve the next generation of solutions which might enrich the physicality of HCI?

Hence, for this dissertation, I selected a portfolio of five publications that represent the research that I undertook during my PhD, each driven by serving the aforementioned vision in some manner. Each of these projects investigates and/or proposed HCI designs or related scaffolding that foreground movement and embodiment, while dealing with distinct technologies, application domains, methodologies, and research contributions. Admittedly, these projects do not stand as representative of a monolithic research program, as the integrity, efficacy, and situatedness of each work in itself was prioritized at the time of publication, rather than cohesion. However, they are al informed by the discourse on movement and embodiment in HCI/IxD literature and driven by serving the vision of diverse physicality in HCI.

By revisiting these projects and reflecting on them using a vocabulary derived from salient aspects of embodiment in HCI discourse, I hoped to form the basis of a critique on and implications for the trajectories of both technologies and discourse that aim to enrich the physicality of HCI. In previous chapters I have laid out reflections on how each research project speaks to the interaction of its technological subject matter with the discourse in HCI/IxD, and what insights it reveals in terms of the potentials and shortcomings of theory, technology, and methods. Here, I attempt to consolidate these reflections into commentary that may have bearing on future HCI design.

Discussion

First, a brief recollection of some of the points that came up while reflecting on each of the research projects compiled in this dissertation:

1. While my study on the perception of electronic music held up as an academic exercise, it did not yield consequential insights that could inspire or otherwise inform any concrete design work. This pushed me to study the epistemology and methodologies of modern HCI, which informed my subsequent work.

2. Following our exercises in design education for gestural interfaces, I came to realize the the materiality of gesture sensing was not fully developed. The technology itself did not stand as a design material, as its constraints and affordances for making and engaging hinged on the particularitites of implementation.

3. The experience of developing LabDesignAR and offering it to potential users showed me two things: First, while augmented reality could serve to create interesting experiences for a single individual, the inability to construe a compelling and dependable intersubjective experiences hindered its potential in many use cases that initially looked promising. Second, capturing and evaluating the user experience in a methodologically solid manner was a significant challenge, which led me to appreciate contemporary HCI approaches that draw from the arts.

4. The project on computational heirlooms was a successful exercise in using prose to construct and communicate a design concept. With

this project I also turned to physical materials as a basis for user experience, and synthesizing an integrated understanding of physical and digital materials allowed me to reflect back on my earlier work for new insights.

5. Finally, the project on social drones considers an actuated design material, which opens up additional layers of meaning as people engage with it on a social and emotional levels.

Collectively, these insights and reflections can serve towards addressing a number of questions to inform future work on effective and compelling embodied interaction designs.

What criteria are relevant for embodied interaction designs, and what knowledge can guide their realization? My experience in the research projects presented in this dissertation suggests that the five notions—integration, primacy, subjectivity, intersubjectivity, and materiality—might serve as preliminary criteria for embodied interaction. Building on the design guidelines and frameworks laid out in previous work (covered in the chapter on Theoretical Foundations), these notions represent a novel contribution in two ways: First, while previous work often treats topics of tangibility, materiality, human movement, and movement within the designed system as separate concerns, this vocabulary addresses embodied interaction holistically. It is no accident the the first of these constructs describes the *integration* of movement and embodiment. Second, while previous work often focuses on providing knowledge to inform a design process and actions to be taken by designers, the vocabulary that I propose relates primarily to properties of the interactive system and qualities of the interaction design. Of course, in order to properly serve this purpose, ideally, the way in which the five notions are articulated must be further refined, illustrated by examples and counterexamples, and evaluated in use. I have left these efforts to future work, as in this dissertation I opted to focus on providing a candid and reflective account of how these ideas came into being.

What methodologies in HCI are relevant for embodied interaction design? The five research projects covered in this thesis have made use of the gamut of epistemological commitments and methodologies that have found their place in HCI literature. While HCI has a history of less than half a century in the academic space, and its nature has changed drastically over this short period of time. This progression is often read as happening through three waves,[51] periods (Classical, Modern and Contemporary),[52] or paradigm shifts (Positivist–Postpositivist, Constructivist–Interpretivist and Critical–Ideological)[53] that correspond to clusters of intellectual commitments. The way that I understand and conduct HCI/IxD scholarship, throughout the research activities that culminated in this thesis, developed in a manner that tracks this histor-

[51] Bødker, S. (2006). When Second Wave HCI Meets Third Wave Challenges. In *Proc. NordiCHI '06*. ACM; and Bødker, S. (2015). Third-wave HCI, 10 Years Later—participation and Sharing. *interactions*, 22(5):24–31

[53] Duarte, E. F. and Baranauskas, M. C. C. (2016). Revisiting the Three HCI Waves: A Preliminary Discussion on Philosophy of Science and Research Paradigms. In *Proc. IHC '16*. ACM; and Harrison, S., Sengers, P., and Tatar, D. (2011). Making epistemological trouble: Third-paradigm hci as successor science. *Interacting with Computers*, 23(5):385–392

[52] Rogers, Y. (2012). HCI Theory: Classical, Modern, and Contemporary. *Synthesis Lectures on Human-Centered Informatics*, 5(2):1–129

ical evolution of the field. Among these various ways of interpreting the history of the field, personally, I have found Koskinen et al.'s 2011a description of the progression of design research through the lab, the field, and the showroom to be the most useful.[54] With regard to embodied interaction, what I experienced through the projects compiled here was that the "lab" and "field" methodologies need a prohibitive degree of sophistication on part of the researcher in order to generate insights that can inform design. This is not to say that it would be impossible to do lab and field studies to inform embodied interaction design—and many scholars have indeed done just that—but they need to be practiced with utmost care. As far as my own research goes, while the projects presented here do not properly make use of any artistic or speculative design methodologies, I am convinced that such approaches are well-positioned to capture the primal and subjective qualities that are essential in embodied interaction; and I am intending to orient my future research in this direction.

[54] Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., and Wensveen, S. (2011a). *Design Research through Practice: From the Lab, Field, and Showroom*. Elsevier

Based on the lens of five concepts presented here, how can we address the shortcomings of current theory and technology? As stated above, the vocabulary of five concepts I presented in this thesis has shown potential in terms of articulating desirable qualities in embodied interaction design, and to serve as criteria for evaluating such designs. Future work can address developing this vocabulary into a framework for design, and extracting actionable design implications that point out how these theoretical constructs may be realized in concrete design instances. With regard to technology, in my view, the trajectories of miniaturization and increase of computing power are fairly deterministic, and will eventually significantly increase the quality of interactive materials covered here (i.e. gesture sensing, augmented reality, wearable devices, and drones). A more interesting question is how to design with these technologies as they are. Here, my experience suggests that foregrounding notions of primacy and materiality can be the key to compelling user experiences with these technologies. One corollary that has been intriguing me is, rather than trying to hide or ignore the technical shortcomings of our design materials, to try and make them explicit. In future work I aim to explore design strategies, for example, to make technological limitations and breakdowns more explicit to the user.

Conclusion

This dissertation, based on a portfolio of five research projects, aimed to contribute a critique on and implications for the trajectories of technologies and discourse aimed at enriching the physicality of HCI. Towards this end, reflecting my experiences with the five research projects, I tried to arrive at insights that relate to (1) how the discourse on movement and embodiment in HCI speaks to current emerging technologies, and (2) how the potentials and shortcomings of the current technological and theoretical landscape can be articulated to serve future solutions that might enrich physicality in HCI. To facilitate these reflections, I utilized a vocabulary of five concepts that distill the essence of how movement and embodiment are treated in HCI literature.

The commentary that prefaces the five research publications in the previous chapters gives reflections that pertain to each research project. These are subsequently discussed above, where I recall insights from each individual project and attempt to synthesize them as responses to salient questions. Collectively, these constitute a critique on and implications for the trajectories of technologies and discourse aimed at enriching the physicality of HCI. The principal contribution that emerges from this critique is the five notions I have proposed to distill the treatment of movement and embodiment in HCI, which have the potential to serve as criteria and be developed into a framework for design. The novelty of this contribution lies in that the theoretical constructs proposed here address movement and embodiment in HCI in a unified fashion, and pertain to properties of interaction design artifacts rather than the design process.

The compiled research papers themselves report on various results and pointers for future work. However, to me, an essential result has been the *first-hand experience* of having worked with a multitude of technologies and approaches that have been promoted as enablers for embodied interaction with computers. This experience, for me, has resulted in a new vision that can guide my future work.

This new vision hinges on moving towards a more mature—but also more creative—understanding of the affordances of the technologies that I have worked with. With the vocabulary I proposed here, I feel that I am finally able to look behind the space of possibilities that I envisioned initially. Instead of molding technology to mimic our experiences with the world as we know it, I believe we will be better served by embracing these limitations and designing *with* them, rather than *around* them.

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