SPATIAL COGNITION BASED DESIGN OF EMBODIED INTERFACES FOR ENGAGING SPATIAL COGNITION

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SPATIAL COGNITION BASED DESIGN OF EMBODIED INTERFACES FOR ENGAGING SPATIAL COGNITION

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This dissertation is dedicated to Munchie Bone the Blues Dog and everyone who ever loved her: the set of folks without whom I would never have started nor completed this very strange quest.

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SUMMARY

In this dissertation, I apply research from cognitive science that describes the roles that people's bodies play in their perceptions and mental representations of spaces to the design of tangible and embodied interactive systems as way to further the discussion about the role of space in the design and criticism of digital media artifacts. I begin by introducing the concept of space as it relates to digital media and provide the background from embodied cognition and tangible and embodied interaction (TEI) needed to develop my arguments.

I then critique several important TEI systems from a spatial cognition perspective. I define a design space, which link scales of spatial cognition with scales of embodied interactions, by drawing out the relationships between the specifics of embodied interactions and the ways that TEIs leverage the relationships between bodies and spaces.

I then provide a set of design guidelines that highlight design considerations for TEIs that support, augment, or alter aspects of spatial cognition. These guidelines focus on ways that interventions link the ways that TEIs establish embodiment with the aspects of spatial cognition that they engage.

Finally, I present two case studies, emBodied Digital Creativity and Tangibles for Augmenting Spatial Cognition, which illustrate the application of my guidelines to the development of interfaces that alter mental rotation and perspective taking skills and expand the design space of embodied interfaces that engage spatial cognition.

CHAPTER 1
INTRODUCTION

Space is important to digital media. Some of the earliest computational systems simulated the physical properties of environments and the behaviors of objects in them to aide in targeting anti-aircraft weapons, and as soon as computers could render content on graphical displays, developers created games like *Spacewar*, which simulated gravity and momentum as part of a battle between two space ships that are also in danger of being sucked in to a massive star (Graetz 1981). As the digital medium developed, discussions of the role of space have come from several different directions: cyberspace, virtual environments, and narrative. Each of these points of view handles space differently, but all of them, to some degree, share the opinion that space is fundamental to how we engage with the world, and therefore should play a fundamental role in how we design digital media systems and content.

This document presents research based on an approach that draws inspiration from the cognitive sciences in order to inform the design of interactive systems that can then be used to inform research in the cognitive sciences. While I focus on the contributions this approach makes to digital media, specifically the design of embodied interactions, the research presented here has already led to contributions to cognitive science research as well. As a next step in the discourse related to space and the design of digital media artifacts, this dissertation looks at the fundamental aspects of how humans perceive and act on space, defines a design space for digital media artifacts that engage spatial cognition through these fundamental approaches, and defines a design process that can be

used to develop similar interfaces, while providing examples and necessary background information along the way.

Motivation

In *Hamlet on the Holodeck*, Janet Murray includes "spatial" as one of the four affordances of digital media (Murray 1997). The early definition of the spatial affordance of digital media focuses on the ability of computational systems to present navigable spaces in the service of narrative. Regardless of the focus on narrative, Murray states that the spatial affordance of the digital medium is unique because the spaces it creates are navigable, and therefore can be comprehended in the same way as real spaces (Murray 1997). More recently, Murray has broadened the focus of her discussions of the spatial affordance to include several different ways it is applied to the design of digital media artifacts: containers, landscapes, maps, culturally defined places, and visualizations (Murray 2011). In inventing the medium, Murray describes examples and design elements that use each of these types of spatial representations to engage users of digital media; however, even though Murray states that the illusion of a navigable space is supported by the consistency of the rules that underlie it and that it is up to a designer to balance the foundational aspects of a digital space with a user's expectations brought over from the real world and the requirements of the interface, she spends very little time discussing what those rules are and how different applications of those rules affect a user's experience of the system. As this document will reveal, many of these applications of the spatial affordance may also be applications or appropriations of the cognitive mechanisms that underlie our experiences of real spaces and our understanding those

cognitive mechanisms can lead to new ways to apply the spatial affordance to the design of digital media systems.

Murray's description of navigable virtual environments shows up again and again in digital media theory. Michael Nitsche developed a thorough theory of what he calls video game spaces. Through analysis of video games that are "available on consumer hardware" and that "offer navigable 3D environments", Nitsche develops a holistic description of the aspects of the systems, the games, and the spaces that interrelate to create a player's experience (Nitsche 2008). Nitsche analyzes the experience of the player using five conceptual planes: rule-based, mediated, fictional, play, and social. The play space, for example, is the physical environment and the objects in it (including the player) that playing a video game occurs within. Like Murray, Nitsche considers the ability of the player to navigate the virtual environment as essential to the creation of a sense of presence within that environment. However, Nitsche notes that the creation of presence is not entirely an effect of navigability:

> *All these fundamental techniques to increase the placeness of a digital world remain unexplored, and the experience turns more into a visit that is not supposed to leave any imprint [on the virtual environment]. (Nitsche 2008, 206)*

Video game spaces respond to the presence of the player to varying degrees, and consequently create an experience of presence to varying degrees. While Nitsche's focus on the impact of each element in a video game system leads to a holistic description of the ways that video game spaces create an experience, limiting the analysis to games that use commercially available hardware means that the controller and the physical

environment play a limited role in the discussion of how that experience is created. This dissertation specifically focuses on custom control devices in various real spaces with the intention of uncovering the role that physical space and interaction design can play in the design of digital media systems that create encounters with space (real or virtual).

Inspired by the portmanteau in William Gibson's *Neuromancer*, Michael Benedikt edited a book of chapters speculating about "cyberspace" (Gibson 2000; Benedikt 1991). In his essay "Cyberspace: Some Proposals", Benedikt defines and discusses several rubrics and principals that describe the relationships between cyberspace and real space, one of which is the principle of transit:

> "[the] principle [of transit] states that *travel between two points in cyberspace should occur phenomenally through all intervening points, no matter how fast (save with infinite speed), and should incur costs to the traveler proportional to some measure of the distance*" (Benedikt 1991, 168).

At the time of its writing, 3D graphics and the Internet were in their infancies and Benedikt saw an opportunity in their combination. The examples Benedikt gives of cyberspace are firmly rooted in their time. The authors of *Cyberspace* often describe it as physical representations of digital content that are navigated through as if they were real objects in real space. The vision, however, tends to admit that the true form of cyberspace is yet to be dreamt:

> "*On the largest view, the advent of cyberspace is apt to be seen in two ways, each of which can be regretted or welcomed: either as a new stage in the etherealization of the world we live in, the real world of people and things and*

places, or conversely, as a new stage in the concretization *of the world we*

dream and think in, the world of abstractions, memory, and knowledge"

(Benedikt 1991, 124).

This statement hints at the fact that humans might not always be entering cyberspace, but that cyberspace could also enter reality, as we have seen with things like fitness trackers and self-driving cars. However, the translation from the virtual to the physical cannot adhere to the same rules that Benedikt prescribes for the VR World Wide Web. Internet of Things interfaces inherently must work within the rules of real space. However, understanding the way those rules are related to human cognition and applying that understanding to the design of digital media interfaces can successfully bridge the physical and digital worlds.

In order to describe the ways that people might encounter digital media in the real world, digital media theorists often invoke the term "embodiment"; however, "embodiment" does not always mean the same thing when used to describe digital media. In order to develop a definition of "embodiment" as it is used in this document, I develop the concept from a phenomenological perspective and present an example of the different ways it has been applied in digital media discourse.

The philosophical discipline of phenomenology describes the nature of human experience as the outcome of the relationship between the body, the objects in the world and intentionality. In *Phenomenology of Perception*, Maurice Merleau-Ponty develops the concept of the body-image, the ways by which a person knows where his body is and how it is acting:

…[M]y body appears to me as an attitude directed towards a certain existing or

possible task. And indeed its spatiality is not, like that of external objects or like

that of 'spatial sensations', a spatiality of position, but a spatiality of situation. If

I stand holding my pipe in my closed hand, the position of my hand is not

determined discursively by the angle which it makes with my forearm, and my

forearm with my upper arm, and my upper arm with my trunk, and my trunk with

the ground. I know indubitably where my pipe is, and thereby I know where my

hand and my body are …(Merleau-Ponty 1996).

In this description, the body is conceived of, from a first person point of view, in terms of

its encounter with the environment, and in some ways a body is inconceivable outside of

the ways in which it relates to the world. For humans, from Merleau-Ponty's point of

view, there is no such thing as disembodiment. This concept of the body-image leads to

the idea of the phenomenological encounter, which encompasses the entirety of the

experience of acting in the world. The objects in the world, the body's ability to act on

those objects, and the intentions that bring those actions to bear all inform each other,

ultimately constructing the experience of conscious life.

Dreyfus draws from this construction of experience to draw out three ways that the

concept of the body can be informed by intention and objects: innate structures, basic

general skills, and cultural skills (Dreyfus 2012). Innate structures are the physical

aspects of the body that are used to act in the world: hands grasp, legs walk. These are,

essentially, shared amongst all humans. Basic general skills are the actions that are cross

cultural, and their executions are elicited by the presence of objects, although they are not

performed in the same ways across cultures. For example, the act of sitting is performed

by humans. Cultural skills are actions that are specific to particular cultures and are acquired and performed in the presence of objects that afford them from a cultural perspective. Dreyfus uses the example of sitting in chairs to show how cultural knowledge leads to action. Chairs afford sitting to humans from western cultures that do sit in chairs; however other cultures, that do not use chairs, do not perform the act of sitting based on the presence of chairs. Therefore, sitting in a chair is a cultural skill (Dreyfus 2012). Dreyfus applies these distinctions to a discussion of skill acquisition as it relates to the development of neural nets, a structure used in the development of artificial intelligences, and makes the claim that neural nets, which on their own only allow for thinking, cannot learn or perform tasks in human-like ways, without at least being attached to a perceptual system and preferably embedded in a robotic body with ability to act on the objects in the world.

In "Thinking Hot", Crawford applies the idea of the phenomenological encounter to the practice of design (Crawford 2015). By delving in to philosophical accounts of the practices of making, e.g. woodworking, blacksmithing, etc., Crawford illustrates how design, in practice, involves not only the actions taken by the designer, but also aspects of materials, like the grain of wood, and the contexts of production, whether the object is produced in a factory or a private workshop. Each of these elements informs the design decisions through the concepts of risk, prehension, sympathy, and immanence. Broadly, each concept describes a way in which the actions taken during design, the materials used in that design action, and the objects that are the result of the design inform both the practice of design and the experience of that design practice. For example, risk describes the ways in which design and work unfold over time. Crawford states, "… a

workmanship of risk must grapple with divergent possibilities enabled and demanded by material, tools, and skills" (Crawford 2015). The fact that work occurs over time and involves aspects of the body, objects, and intentions leads to divergent possibilities, which it is up to the designer to balance, based on his experience of the encounter as it unfolds. In this way, the process of design moves away from its traditional definition of a brain solving problems and expressing those solutions to work. Instead, design falls within the realm of the phenomenological experience, and becomes embodied by involving physical elements of the world and their relationships with the body to the process.

Based on the philosophy of phenomenology, Paul Dourish develops the concept of embodiment as it relates to digital media in his 2001 book, *Where the Action Is* (Dourish 2004). Dourish uses the concept of embodiment to describe the ways that digital interactive systems relate to phenomenological encounter by engaging different aspects of that encounter, which relate the aspects described by Dreyfus: the physical body, the physical forms of the objects in the environment, and the sociocultural context of the encounter. Dourish's discussion of the differences between the use of physical and digital patient cards in hospitals illustrates these embodied aspects of a phenomenological encounter. Starting from the sociocultural context, the patient cards are part of the social life of the hospital. The cards relay information between caregivers, and those caregivers approach the cards with a particular set of expectations, based on experience and acculturation, which lead to the particular ways they are used. The physical forms of the cards provide cues related to their use, and changes in that physical form over time provide nuance to the information that they contain. These cards show wear and tear

based on how often they have been handled, which indicates to doctors how sick a patient might be. Similarly, pencil marks and pen marks mean different things on these cards (Dourish 2004). Therefore, the physical changes of the cards embody a certain kind of information that would not necessarily be captured in the written annotations. Finally, the ways these cards engage sociocultural knowledge and embody invisible information would not exist without the ways that the cards are engaged with by physical bodies. A card waits by the patient's bedside until a caregiver comes along and perceives it. It is then grasped, read, annotated, shuffled, handed back and forth, clipped, rehung and eventually filed away. The physical presence of the cards leads to these physical interactions, which, of course, are informed by context and content, but nevertheless supply the foundations, along with the presence of bodies and intentions, for the phenomenological encounter in which they take part. Taken all together, these aspects of embodiment lead to the phenomenological encounter, but each plays its own role in the embodied aspects of that encounter.

Embodiment, then, can take on one, or all, of the following definitions, especially as it has been used in digital media theory:

- The expression of the sociocultural expectations evident in the physical form of the object and the actions that context elicits.
- The physical form of the object itself, including the ways that that objects changes over time through use.
- The physical aspects of the object, which dictate the terms of engagement by a human body.

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While all interactions with digital media systems encompass the entirety of a phenomenological encounter, this dissertation focuses, in particular, on designing systems that engage the physical body in particular ways. Therefore, embodiment, as it is used in this document, refers to the physical elements of an interface that make it possible for a human body to interact with it. The embodiment element of tangible and embodied interfaces are only part of the entire encounter they create, as will be made clear in the discussion of the design space defined in Chapter 5, but it is useful to describe it on its own when analyzing the interactions and design decisions related to it.

Research about tangible and embodied interaction (TEI), which is described in detail in Chapter 2, has led the charge on the role of embodiment in the design of interactive systems. Given the current interest in the role of the body in digital media interactions and the historical interest in the ways that space and digital media are related, this dissertation applies ideas from cognitive science and HCI to investigate the ways that digital media systems that include a physical aspect can be designed to leverage, support and augment human cognition of space.

Research Question and Claims

Given the importance of space to digital media theory and the current trend in TEI research investigating the role of the body in interaction design, I draw from fields of cognitive science and interaction design to answer the following research question:

How are the various aspects of spatial cognition and the design of tangible and embodied interfaces linked through embodiment?

In response to this research question, I make the following claims:

1. TEIs can be described and classified in terms of their relationships to spatial cognition and how they engage the body.
2. Spatial cognition research provides a foundation for designers interested in establishing embodiment in TEI systems.
3. Spatial cognition and spatial skill evaluations provide a foundation for evaluating TEI systems that attempt to leverage spatial cognition.
4. TEI systems that establish embodiment and leverage spatial cognition can engage, support, and augment spatial cognition in ways that take advantage of the unique qualities of the digital medium.

Contributions

In order to support my claims and answer my research question, I make the following contributions to the field of tangible and embodied interaction design and digital media broadly:

1. A spatial cognition-based critique of previous TEI systems, showing how TEI has previously incorporated spatial skills in support of task completion, interaction design, or as an instructional element.
2. A framework that describes how TEI systems establish embodiment and engage spatial cognition based on the scale and the content of the interaction.
3. A set of guidelines for designing TEI systems that establish embodiment based on aspects of spatial cognition.
4. A set of guidelines for designing digital media interventions that engage, support, or augment spatial cognition.
5. A set of criteria for the evaluation of TEI systems that establish embodiment and engage spatial cognition.

Summary

This dissertation defines a design space and a set of guidelines for tangible and embodied interactive systems that support aspects of spatial cognition through the design of interventions. Chapter 1 frames this research in the discourse about space as it applies to digital media. The contributions of this research relate to space as it has been described by scholars including Janet Murray, Michael Nitsche and Michael Benedikt and furthers that discussion by showing that incorporating body movement in the design of interactions and interventions leads to new ways to exploit space in digital media.

Chapter 2 presents background research from the fields of tangible and embodied interaction and embodied cognition upon which I base my claims. Research related to TEIs show how digital media interfaces can engage the body in interactions with digital media systems and develops theoretical discussions about how those interactions change the way that interfaces are designed, classified, and evaluated. Embodied cognition research contributes examples of how the body relates to cognition and provides techniques and tools for evaluating that link.

Chapter 3 focuses specifically on the relationship between the body and cognition of space. I present several examples of aspects of spatial cognition and describe experiments that show the ways that body movements can influence the way that people perceive objects and spaces, navigate large scale environments, and operate on mental representations of objects and their spatial properties.

In chapter 4, I draw from the research presented in chapter 3 to analyze TEIs that engage different aspects of spatial cognition. I break TEI interactions in to three categories related to the scale at which an interactor engages with them, figural, vista, and environmental, which are drawn from cognitive science research. I describe the qualities of interaction that interfaces at each scale incorporate and describe how those interactions, along with the interventions that they support, engage aspects of spatial cognition.

In Chapter 5, I define a design space and a set of guidelines for developing TEIs that engage aspects of spatial cognition through the combination of embodiment and intervention. The design space plots TEI systems along three axes: establishing

embodiment, designing interventions, and the aspects of spatial cognition that the systems engage. The guidelines describe key design decisions and relationships that designers must keep in mind to develop TEI systems that fit within this design space.

Chapter 6 includes discussions of two case studies from my own work which exemplify the design process presented in chapter 5. The emBodied Digital Creativity project improves mental rotation ability by mapping body movement on to a virtual avatar using a tangible puppet controller which is used to control a game in which players must continuously perform mental rotation to adjust to a novel rotating environment. Tangibles for Augmenting Spatial Cognition leverages virtual reality, hand tracking and tangible objects to create an intervention that engages perspective taking ability.

Finally, chapter 7 concludes the document with a discussion of my research contributions, future work and the broader impacts that my contributions have across disciplines including science, technology, engineering and mathematics education, embodied cognition research, tangible and embodied interaction design, and artificial intelligence.

CHAPTER 2
BACKGROUND

This research draws from two main areas of research: tangible and embodied interaction (TEI) and embodied cognition (EC). This chapter describes the relevant background needed to position this research within the context of each of these fields.

Tangible and Embodied Interaction and Frameworks

The field of TEI grew out of human computer interaction (HCI) research, which broadly seeks to study and design the ways that people use digital technology, from the electro-mechanical controls of early airplane cockpits to the mice and keyboards of personal computers. Many of the earliest human-computer interfaces hint at the coming of tangible computing. Doug Engelbart debuted the mouse in 1968 during the Mother of All Demos, which, along with the original graphical user interface, made it possible for people to point at and move digital content, effectively enabling people to use spatial skills to orient themselves to their digital work (SRI International 1968). The first stylus appeared even earlier, allowing people to draw lines and curves on screens (Sutherland 1964). Both of these devices make it possible for people to use their bodies in ways that they have already learned – pointing or drawing – as a way to manipulate digital content.

By the 1990s, HCI researchers began to see the potential for incorporating digital technology in to the objects that we encounter on a regular basis and Mark Weiser coined the term "ubiquitous computing" to refer to the eventual inclusion of technology in all the objects that we engage with on a day to day basis (Weiser 1999). If the concept of ubiquitous computing were to come to fruition, computers would take on countless

shapes, and people would interact with them in countless ways. This line of thinking lead

to Durrell Bishop's "Marble Answering Machine", which is commonly cited as one of

the first tangible interfaces (Poynor 1995). The marble answering machine represented

phone messages with marbles, which were placed in a particular spot to be played back.

People could easily see how many messages there were, and saving a message was as

simple as not putting the marble back in the bin. This kind of use of physical form and

manipulation to engage with digital content laid the foundations for tangible and

embodied interaction as we know it today. In 1995, Fitzmaurice, Ishii, and Buxton

created "Graspable Bricks", which focused on translating elements of graphical user

interfaces in to physical objects and on designing physical interfaces with affordances

that support the different gestures and manipulations possible with the human hand

(Fitzmaurice, Ishii, and Buxton 1995). Fitzmaurice et al. cite the following benefits of

graspable user interfaces, many of which still form the foundations of TEI research:

- *It encourages two handed interactions;*

- *Shifts to more specialized, context sensitive input devices;*

- *Allows for more parallel input specification by the user, thereby improving the expressiveness or the communication capacity with the computer;*

- ***Leverages off of our well developed, everyday skills of prehensile behaviors for physical object manipulations;***

- *Externalizes traditionally internal computer representations;*

- *Facilitates interactions by making interface elements more 'direct' and more 'manipulable' by using physical artifacts;*

- ***Takes advantage of our keen spatial reasoning skills;***

- *Offers a space multiplex design with a one to one mapping between control and controller; and finally,*

- *Affords multi-person, collaborative use.*
(Fitzmaurice, Ishii, and Buxton 1995) emphasis added by the author.

These advantages, however, are not solely due to the "graspability" of the interface, and as further research and design has shown, they derive more from the quality of the interaction than from the existence of a set of physical objects. To account for the breadth of possibilities for interaction design in this context, Ishii and Ullmer coined the term "Tangible User Interface" (TUI) to describe interfaces that "augment the real physical world by coupling digital information to everyday physical objects and environments." (Ishii and Ullmer 1997). This definition allows for the digital content to exist at different scales, beyond just objects that are within reach and can be grasped. To illustrate the breadth of this definition, Ishii and Ullmer describe three tangible user interfaces: metaDESK, transBOARD, and ambientROOM. The metaDESK is a tabletop computing interface that uses physical objects in place of the elements of standard GUI interfaces like windows and handles for interacting with data. The transBOARD is an augmented whiteboard, which places digital content within view of multiple people and makes it possible to annotate, sketch, and display hybrid physical digital content using tangible objects and pens. The ambientROOM is an office or building outfitted with devices which make digital content available at the periphery of a person's attention, thereby bringing useful information, which otherwise may not be readily available, in to a space without detracting from the focused work that is taking place (Ishii and Ullmer 1997). While these examples clearly accomplish moving digital content and interaction away from a single central location, they also, obviously, are not all tangible. However, with respect to the topic at hand – space and embodied interaction – they do directly

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correspond to one way that space has been defined in terms of its relationship to the body – scale: figural (metaDESK), vista (transBOARD), and environmental (ambientROOM). The fact than an interface does not have to be touched in order to accomplish the goals of graspable or tangible user interfaces has led to a further broadening of the field and the term tangible and embodied interfaces (TEIs).

Several frameworks have been proposed to describe how TEIs relate digital content and interaction. One of the earliest attempts to explain how tangible interfaces do what they do extended a paradigm from software development, the model; view; controller framework, which separates function and analysis from presentation and interaction in the design and development of GUI interfaces. Ullmer and Ishii proposed the Model, Control, Representation (physical and digital) model for TUIs, which described tangible interfaces as objects that couple control and representation of digital content in a single interface (Ullmer and Ishii 2000).

Over the years several researchers have developed additional frameworks that describe various aspects of the design and development of tangible and embodied interfaces (Fernaeus, Tholander, and Jonsson 2008a; Fishkin 2004; Mazalek and van den Hoven 2009; Shaer and Hornecker 2010; Sharlin et al. 2004; Ullmer and Ishii 2000). Fishkin proposed a taxonomy for describing TUIs that placed them along two axes: metaphor and embodiment (Fishkin 2004). In this taxonomy, embodiment refers to the relationship between the digital content and the interface, i.e. whether the content is completely contained in the interface or displayed separately. The four levels for this characteristic are full, nearby, environmental and distant. This taxonomy indirectly takes in to account the body/position of the user with respect to the interface and the content; however, the

primary focus is on the relationship between the input and output devices and not the body of the user.

Fernaeus et al. in 2008, defined a design framework based on the "practice turn" in the field of HCI, which broadly refers to a trend in HCI that focuses on designing interfaces that support the way people already do things with their bodies (Fernaeus, Tholander, and Jonsson 2008a). The authors go on to describe the "practice-oriented perspectives" as "reject[ing the] separat[ion of] mind from body" (Fernaeus, Tholander, and Jonsson 2008a). While the authors engage more with the philosophy of phenomenology than cognitive science, they do follow a common thread: people's actions and the context of that action influence their comprehension of content and vice versa. They describe four moves that the design of interactive systems makes because of the practice turn and a few implications for designers, one of which is "representations as resources for action". This is a broad suggestion but involves taking in to account the context of an interaction, a user's expectations of how things happen in that context, and a designer's sensitivity to both of those things while creating an interface that accomplishes its goals. While this discussion does include concepts of embodiment as important elements to consider when designing interactive systems, there is a lack of depth in its descriptions of how the body, context and design integrate.

Other TEI frameworks deal with concepts of embodiment in a similarly non-specific way, often focusing on the embodied aspects of social situations or on the affordances of embodied interfaces. In 2006, Hornecker and Buur presented a framework for describing the social aspects of tangible interfaces, which includes embodied facilitation and spatial interaction as categories (Hornecker and Buur 2006). However, these categories focus on

the form of the interface and how tangible interfaces fit in to the real world, as opposed to how the user's expectations of the real world can be used to design interfaces. Klemmer and Takayama propose five themes relevant to the design of interactive systems, one of which is "thinking through doing" (Klemmer, Hartmann, and Takayama 2006). "Thinking through doing" focuses on the relationship between the mind and body as it relates to learning and problem solving. This theme is strongly related to Kirsch's ideas of epistemic and pragmatic actions and the authors describe several ways that interfaces can support thinking through doing such as including gestural interactions and designing interfaces that support body movement (Kirsh 1995; Klemmer, Hartmann, and Takayama 2006). The discussion stays at a high level, and does not look at the specific design elements that tangible interfaces can employ to facilitate the themes. Sharlin et al. include successful spatial mappings as part of their discussion about designing successful TEIs (Sharlin et al. 2004). The authors claim that spatial qualities of objects and environments are a fundamental part of how humans perceive and interact with them. Based on Norman's definition of affordances, the authors describe successful spatial mappings as aspects of TEI interactions that can be understood based on the relationship between form and function and denote TEIs that combine successful spatial mappings with applications that focus on manipulating spatial qualities as "spatial TUIs" (Sharlin et al. 2004). The authors focus on matching the degrees of freedom of the input and output space for creating successful spatial mappings and present several interfaces that create strong one-to-one mappings between input and output; however, they do not go beyond degrees of freedom by looking at other spatial relationships that could be useful for interaction design.

This lack of specificity and depth is shared by most frameworks, many of which identify

themes and concepts that are important for tangible interaction designers but then fail to

unpack them in detail or give specific direction for how to approach designing with the

themes in mind. There are many reasons for this lack of depth. For the most part, further

specificity has been out of the scope of taxonomies of tangible interfaces, and if

researchers were to continue to dive deep down a single theme, they would end up with a

sort of framework-fractal that goes on forever describing decisions that designers might

face. However, the space these frameworks leave open provides an opportunity for more

in depth research, and recent research from embodied cognition gives insight in to how

the body, its actions, and its context relate to interpretations of objects and information,

which can now be included in a more nuanced description of design decisions that

incorporate theories of embodiment.

One framework in particular delves in to the details of the role of the body in tangible

interaction. This framework divides embodied cognition in to three "flavors" relevant to

the design of TEIs: distributed representation and computation (DRC), socially situated

practice (SSP), and sensorimotor coupling and enactment (SCE) (van Dijk, van der Lugt,

and Hummels 2013). Each of these flavors plays a role in the design of an embodied

interactive system, and the authors ultimately show how each flavor, on its own, is

insufficient (or even problematic) to take full advantage of embodied interaction.

However, DRC and SSP still only relate to embodiment in that they give physical form to

some formless information, either a representation of data, or a set of social practices.

While all three flavors are indeed important facets of the design of interactive systems,

SCE underlies the ultimate benefits of including digital media in tangible and embodied

interactive systems. DRC and SSP are consistently accomplished with non-digital objects and spaces, and while without SCE our behavior in a non-digital world would be much different, the ability of digital media to augment the non-digital world derives from the coupling between our sensorimotor system and our understanding of the places, people and things that populate the world. Understanding the fundamentals of SCE and applying them to the design of interactive systems is an important step in creating digital media that makes it possible to do things and think in ways that were previously uncommon or impossible.

The progression of focus in the field of TEI from tangibility and the physical representation of data to the broader questions of how the elements of embodiment can be designed for has led to several large open questions. One of which is posed by van Dijk in his dissertation:

> *If we want to design systems that support the way people make sense of the world around them, the question is whether sensorimotor couplings are going to be enough, or whether sensorimotor theory is mostly useful when designing for 'bodily phenomena', like sports, or feelings of stress. That is, can sensorimotor theory help us get a grip on the more 'cognitive' activities for which we normally would use words like 'remembering', 'thinking', 'representing', 'deciding', 'creativity', 'communication', and so on? (van Dijk 2013)*

This quote simultaneously hints at the strong link between the three flavors of embodied cognition, reveals the types of questions each flavor tends towards answering, and asks

what the contribution of SCE can be to the design of interactive systems that typically focus on questions related to 'problem solving' rather than movements and skills.

While DRC and SSP are both important parts of the theory of embodied cognition, this dissertation deals directly with SCE, and as such, is founded on research that illustrates the ways that the sensorimotor system is directly related to cognition, particularly as it relates the body to space. Furthermore, the common thread throughout this document is that SCE does in fact relate to problem solving, and when engaged with from a spatial cognition point of view, that designers can incorporate it in to their designs as a way to achieve that goal. This research, then, exists in a direct lineage of TEI frameworks and fits underneath the SCE flavor of the framework proposed by van Djik in 2013.

How TEI has addressed spatial problems and cognition

Cognition, and particularly spatial cognition, has been of interest to TEI researchers for years. Related research is often undertaken to show the benefits of using tangible interaction instead of a purely GUI based interface. These studies attempt to look at TEIs not from a usability or technology standpoint, and instead focus on the cognitive and behavioral effects that the TEI has on how the user approaches solving a particular problem.

In 2008, Kim and Maher looked at the effect of tabletop and TUI interfaces on architectural designers solving 3D problems (Kim and Maher 2008). The researchers used a protocol analysis which asked subjects to think out loud while they were performing the design task, which made it possible for researchers to uncover the different strategies used to solve the design problems using either a TUI or GUI. In the

study, participants used an augmented-reality-style-tabletop-interface that displayed virtual building elements at the location of specially marked blocks, and a mouse and a keyboard to control ArchiCAD, a standard architectural CAD software suite. Participants were asked to arrange virtual furniture in a virtual home or office using each interface. The researchers recorded designers' comments about their process during the design task and asked them to recall their processes after they completed the task. Researchers developed a coding scheme and analyzed the data for actions as well as thoughts related to problem solving. Analysis of the results showed that when using a TUI, designers came up with more possible solutions and described those solutions more often than when using a GUI. Furthermore, each action took longer to perform using a GUI than a TUI. When using the TUI, designers revisited previous solutions more often, and the length of time between actions was shorter than when using a GUI, indicating that participants performed more epistemic actions with the TUI interface. Designers using the TUI interface also performed more expressive gestures more often than designers using the GUI interface. TUI users also exhibited increased perception of new and existing "visuo-spatial features" (Kim and Maher 2008).

While this is a well-designed study that does show different strategies, both behavioral and cognitive, being used for TUI and GUI interfaces, the researchers make broad claims, which are not supported by their research:

> *"Through the validation of the hypotheses a final conclusion of this research*
> *is drawn as follows: TUIs change designers' spatial cognition, and these*
> *changes are associated with creative design processes" (Kim and Maher*
> *2008).*

Assuming that epistemic actions are a behavior that is associated with spatial cognition, it is clear from this research that TUIs support spatial cognition; however, the researchers do not ever actually show a change in spatial cognition, only that people employ it differently when using different interfaces.

The work of Kim and Maher essentially represents the state of spatial cognition research in the TEI community. In 2013, Alissa Antle conducted a similar study comparing motor-cognitive strategies for solving a jigsaw puzzle using tangible puzzle pieces or a multi-touch tabletop interface. Her results showed that people using tangible interfaces perform more epistemic actions than when using a touch screen (Antle and Wang 2013). Antle, however, does not make any claims about spatial cognition, and her main focus was creating and applying a coding schema for studying motor-cognitive strategies for tangible interfaces (Antle and Wang 2013).

In 2008, Quarles et al. showed that tangible interfaces compensate for low spatial ability scores for students who are learning to use an anesthesia machine (Quarles et al. 2008). During this study participants took a set of spatial ability tests to establish a baseline spatial ability metric. They used either a tangible interface (TUI), a graphical interface (GUI), or a real world anesthesia machine (PUI) to learn how to operate the machine. They returned a day later and were evaluated on how well they could operate the machine. Even though there were no significant differences in spatial ability scores between the groups, the group that learned using the TUI reported less difficulty visualizing gas flows in the machine. Furthermore, on a written test that assessed the conceptual understanding of gas flows in the machine, the scores for individuals in the GUI and PUI group were strongly correlated with their spatial ability scores, while the

scores of students using a TUI were not correlated. Given that the groups did have significantly different scores on the tests, this result shows that the TUI provided a way for people to learn the concept of gas flow in the machine regardless of their spatial ability (Quarles et al. 2008). Once again, this study does not show an effect on spatial cognition, but it does show that tangible interfaces provide tools that can engage, support, and augment existing spatial cognitive abilities.

Because of spatial cognition's strong link to the body and action, discussed below, and the way that TEIs can act as resources for action, designing TEI systems which create ways for users to leverage preexisting spatial skills clearly has advantages; however, up to this point there has been essentially no research done (aside from epistemic and pragmatic actions) showing what spatial skills TEIs support and how they support them.

Embodied Cognition and Perception-Action Coupling

Traditionally, the cognitive and psychological sciences have presented cognition as occurring entirely in the brain, completely separate from the body. In this model, called sensorimotor theory, the brain acts as a mediator between perception and action by processing information from the senses and then commanding the body to act (Prinz 2005). In these traditional views, information flows in a one-way system from sensation through perception and cognition, to the action system. Inherent in this approach is the notion that the action and body are output systems that simply receive information from perceptual and cognitive systems, and as such are not involved in perception and cognition. However, recent research has indicated that the body actually plays an active role in cognition. The specifics of how cognition, the body and the environment interrelate are continuously under debate, illustrated by the distinctions between the

ideomotor and ecological approaches to cognition (which are outlined below). However, regardless of the mechanism that underlies manner in which the body and action systems can influence cognition, observations from both approaches indicate ways that cognition can be said to be embodied; that is, cognition cannot be separated from the body and is, indeed, embedded within the body and the environment in which action occurs.

The ideomotor approach was originally based on the notion that cognition is derived from intention and led to action after the conditions for its execution had been met. The ideomotor approach predicts a mental representation of the intended action, which itself leads to the production of that action assuming no other mental representation suppresses its performance. The mental representation of the intention is tightly coupled to the mental representation of the changes in the environment and the body that result from that action, i.e., the representation of the effects of the action that are perceived (Prinz 2005). There are two important implications for this tight coupling between action and perception codes – activation of the action system can excite the associated codes in the perceptual system, and activation of perceptual codes can activate the associated movement codes in the action system. In this way, unlike in traditional information processing systems, ideomotor coding provides a mechanism through which the action system can have an influence on perception and cognition (action is an intricate part of perception and cognition and not just a passive recipient of information). Further, because action codes are so tightly coupled with the perceptual results of that action, the ideomotor approach predicts that any perception of a change in the environment that could result from an action can activate the cognitive representation of that movement. As a result, theorists have hypothesized and supported through observation the fact that

perception of a movement and the effects of a movement also activate a mental representation of that movement. Thus, the coupled mental representations of perception and action is the foundation of ideomotor (aka common coding) theory, which claims that there is a shared mental representation of movement and perception, and that these representations are integral to perception and are the basis of action, whether the action is perceived, enacted, or imagined. The section "The Perception and Imagination of Action" highlight this link from both observational studies and interneuron recordings.

On the other hand, the ecological approach to embodied cognition describes the link between the body and cognition without relying on mental representations. Under the ecological approach, action is an emergent property of a dynamic system , in which the perception of the environment, the performance of an action, and the effect of that action on that environment inform each other continuously (Hurley 2001). This approach can be described as a feedback loop that incorporates brain, body, and world in a single system, all of which fall within the broader boundaries of cognition. The nervous system, including the brain, then becomes a network of systems that promote, inhibit, or otherwise influence perception and execution of movement. It is through this approach that cognition can be said to be distributed and environmentally- and socially-situated (Hurley 2001). Tool appropriation and the effect the state of the body has on perception provide good examples of the expected results of the ecological approach.

While the specific cognitive mechanisms by which cognition can be said to be embodied are still under debate, it is not necessary to take sides to apply research from either approach to the design of computational systems. Theories of embodied cognition are constructed from different observed phenomena, which when taken together, support the

claim that the body plays an active role in the ways that humans and other animals make sense of the world. These phenomena include the perception and imagination of action, tool appropriation, and action's influence on perception. Many of these examples have implications for how the body is related to spatial cognition, a subfield which is introduced in some detail below. Specific links between the body and spatial cognition are dealt with in detail in Chapter 3. This section primarily describes what has already been done in support of the claim that cognition is embodied and introduces the field of spatial cognition.

Perception and Imagination of Action

Common coding theory links perception, execution, and imagination of movements through a shared mental representation. The following examples focus on the link between perception and imagination of movements, i.e. when a movement is perceived, it is simultaneously imagined. Research supporting this link has shown that people recognize their own movements and the movements of their friends, even when those movements are represented by an abstract body or points of light (Beardsworth and Buckner 1981; Cutting and Kozlowski 1977), and that painters simulate brush strokes in their motor systems when viewing paintings (Taylor, Witt, and Grimaldi 2012). Similar effects have been observed and supported through direct observation of the firing of neurons in the brains of monkeys (Iriki et al. 2001). Common coding theory also links the body to spatial cognition. People use different cognitive strategies to organize space based on the presence of a body and how objects are arranged (Lozano, Hard, and Tversky 2007).

Other examples show the link between execution and imagination. People spatialize the concept of time as moving forward or backwards depending on how their motor systems are primed (Boroditsky 2000), and they use gestures to support the performance of complex spatial tasks (Morsella and Krauss 2004). These and other phenomena provide a basis for the belief that the motor system plays a key role not only in moving the body but also in the perception and imagination of movements. The fact that the motor system has been appropriated as a part of higher order cognitive processes provides evidence for the link between the body and cognition.

Tool Appropriation

Research on tool appropriation has shown that the use of a tool to perform as task alters both the body schema (an abstract mental representation of the size and location of all parts of the body) and the perception of the body's capabilities. Evidence for these effects comes from interneuron recordings in monkeys during tool use and reaction time and peripheral awareness tests in humans.

In 1996, Iriki et al. showed that neurons in the intraparietal cortex of monkeys that code for body schema change their responsiveness (receptive fields) when the monkeys learned to use a rake to reach for food pellets (Iriki, Tanaka, and Iwamura 1996). Specifically, prior to using the tool, the neurons that respond when a light stimulus is presented on the hand of the monkey, did not respond when light was presented on the rake. After experience using the rake, the neurons that previously only responded when the light was on the hand now also responded when the light was on the rake. This experiment provided evidence that body schema is not only plastic, but that neurons that

encode it change to incorporate objects that are not typically considered part of the body. That is to say, there is physical evidence that tools are appropriated in to the body schema when they are used.

Further research has described different aspects of this tool appropriation phenomenon. Iriki et al. showed that tool appropriation occurs when the hand and tool are only observed on a video screen, indicating that seeing the actual tool is not necessary for appropriation to occur (Iriki et al. 2001). Additional research has shown that the entire length of the tool is appropriated in to the body schema, as opposed to just the end of the tool (Bonifazi et al. 2007). These effects have been shown to be dependent on the intent to use the tool. Passively holding the tool, without the intention to use the tool, does not induce the same appropriation (Iriki, Tanaka, and Iwamura 1996; Kao and Goodale 2009). However, observing tool-use coupled with the intent to use the tool induces the same appropriation as if a subject were to actually use the tool (Costantini et al. 2011).

Many similar effects have been shown through the use of reaction time tests that ask a subject to respond to a flashing light or vibration either on the hand, on some part of the tool, near the hand or tool or somewhere else. The response time before tool appropriation is shorter for a stimulus on the hand as opposed to a stimulus either on the tool or anywhere else. However, after using the tool, the response time for a stimulus anywhere on the tool or very close to it shrinks to nearly the same as for a stimulus on the hand (Kao and Goodale 2009; Jovanov et al. 2015).

This tool appropriation effect illustrates that the brain changes with respect to the body's relationship to its environment and that the body's capability combined with intent is

sufficient to cause this change in short periods of time. Evidence of this relationship

provides support for embodied cognition theory and supports the hypothesis that

embodied cognition research can inform the design of embodied interactive systems.

Action's Influence on Perception

Tool appropriation research has shown that the state of the body affects perception of

flashing lights and vibration stimuli. Additional research in both tool appropriation and

other perceptual effects has shown that the relationship between the body and the

environment changes people's perception of required effort, reachability, distance,

direction, and steepness. Many of these perceptual effects are discussed in detail in

Chapter 3. They are described here to support the use of embodied cognition research for

the design of TEIs.

Jessica Witt links perceptual effects with the body's ability to act in the environment

(Witt 2011). In this way, tool use as well as factors like "… body size, body control and

coordination, energetic potential, and the challenges of the task…" can all have an effect

on perception (Witt 2011). In one case, which combines tool use, difficulty of task and

elements of body control, Witt showed that a batter who is hitting well perceives the ball

as being larger than a batter who is hitting poorly (Witt and Proffitt 2005). While it is not

clear from the study what about the relationship between body and success led to the

perceptual effect, it is clear that the effect is there. Similar self-report experiments have

shown that perceived effort due to age or infirmity lead to altered perception of distance

(Bhalla and Proffitt 1999), wearing a heavy backpacks alters the perception of the grade

of a hill and distance (Bhalla and Proffitt 1999; Proffitt et al. 2003), and that body size

influences perception of distance and height of walls (Witt 2011).

These studies provide evidence for the effect of the relationship between body and

environment on cognition by showing that altering aspects of either affects perception.

Designers of interactive systems may be able to exploit these relationships to alter users'

perceptions of elements of their systems, and given these examples, the physical aspects

of interaction may make these relationships more directly exploitable.

Spatial Cognition

This dissertation focuses primarily on how this relationship between the body and the

environment affects perception and cognition of space. This section provides background

describing the history and current state of the art concerning spatial cognition and the

importance of spatial cognition to how people understand their environment and solve

problems.

Research on spatial cognition has shown that people use different cognitive strategies to

organize space based on the presence of a body and how objects are arranged (Lozano,

Hard, and Tversky 2007), that people spatialize the concept of time as moving forward or

backwards depending on how their motor systems are primed (Boroditsky 2000), and that

people gesture in support of performing complex spatial tasks (Morsella and Krauss

2004). These and other phenomena provide a basis for the belief that the body plays a key

role in spatial cognition.

With its roots in attempts by experimental psychologists to account for human spatial behavior, spatial cognition seeks to define the underlying cognitive mechanisms and mental representations involved in human (and non-human) interactions with space (Denis and Loomis 2006). Mental representation comes up a lot in discussions of spatial ability (and other cognitive phenomena). It refers to a cognitive symbol that corresponds to an object or experience that is not immediately accessible to the body. It is used broadly and does not directly relate to any specific neurological mechanism by which it is produced or accessed. While embodied cognition research has moved away from mental representations as a model of cognitive mechanisms, the observation of particular spatial phenomena remain relevant for cognitive science research and provide glimpses in to how people engage with the objects and spaces they encounter.

As with much of the field of cognitive science, spatial cognition research has firm roots in artificial intelligence research. Early experiments, conducted towards the design of autonomous robots, focus heavily on how space is represented and manipulated in working memory.

More recently, with the growth of the field of embodied cognition, spatial cognition research has started to focus on the role of the body in our relationship to and understanding of space. The embodied aspects of spatial cognition are made clear through phenomena observed by cognitive scientists during experiments. These phenomena include navigation and cognitive mapping (Golledge 1999; Portugali 1996), representations and manipulation of spatial knowledge (May 2004; Mou et al. 2004), linguistic components of spatial representation and memory (Bloom 1999; Hickmann and Robert 2006; Laguna et al. 1996), spatial perception (Avraamides et al. 2004), route

perspectives (Taylor and Tversky 1992; Tversky 2000), and the effects of scale (Hegarty et al. 2006).

Spatial Ability and STEM Problem Solving

Over the last 50 years, research has provided a wealth of evidence showing a strong link between spatial ability and success in STEM domains. In 1957, Super and Bachrach published a report showing that spatial ability was a defining characteristic of successful STEM professionals (Super and Bachrach 1957). However, the exact role that spatial ability played in those individuals was poorly understood. Inspired by this work, several large longitudinal studies were launched to determine the link between students' abilities, academic performances and careers. The Study of Mathematically Precocious Youth (SMPY), begun in 1971, followed more than 5000 students who scored in the top 0.5-3% on the verbal and math sections of the SAT over the course of 4 decades. The results of this study indicate that, while math and verbal abilities are strong predictors of future success in general, spatial ability correlates strongly and adds incremental validity to predictions of interest, participation, and success in STEM fields (Lubinski and Benbow 2006; Shea, Lubinski, and Benbow 2001; Webb, Lubinski, and Benbow 2007). In 2009, Wai revisited project TALENT data collected over 11 years during the 1960s and early 70s from a random sample of 400,000 students. His analysis revealed that the correlation between spatial ability and STEM success holds true for all students (Wai, Lubinski, and Benbow 2009).

Given the importance of spatial ability to STEM success, researchers have begun to look not only at specific spatial abilities, but how the abilities might relate to each other. This research has led to several frameworks for describing spatial abilities. Wai and

Newcombe developed two frameworks which are of particular interest here (Wai, Lubinski, and Benbow 2009; Newcombe and Shipley 2013). Wai outlines a high level psychological framework used in his and others' analyses of spatial ability that splits spatial ability into four different types: three-dimensional spatial visualization, two-dimensional spatial visualization, mechanical reasoning, and abstract reasoning (Wai, Lubinski, and Benbow 2009). Three dimensional spatial visualization refers to ability to mentally fold a two-dimensional shape into a three dimensional object. Two-dimensional spatial visualization is the ability to mentally rotate a 2D figure. Mechanical reasoning relates to the ability to deduce cause and effect in mechanical systems of varying complexity, and abstract reasoning is the ability to determine the rules governing a particular pattern and to apply those rules in other places.

In the paper "Thinking about Spatial Thinking: New Typology, New Assessments", Newcombe and Shipley classify the breadth of spatial abilities in a way that is useful for both relating different spatial abilities to one another and finding links between different types of spatial abilities (Newcombe and Shipley 2013). In their paper, they define four broad types of spatial abilities and provide the following table, Figure 1, which places specific spatial abilities within their framework:

Within-Object (Intrinsic) Spatial Relations (2 static, 4 dynamic)
1. Disembedding: Isolating and attending to one aspect of a complex display or scene.
2. Categorization: Learning categories based on spatial relations.
3. Visualizing 3D from 2D: Understanding 3D spatial relations presented in a 2D image or drawing.
4. Penetrative thinking: Visualizing spatial relations inside an object.
5. Mental transformations: Visualizing how an object will change over time
6. Sequential thinking: Visualizing the product of a series of transformations.
Between-Object (Extrinsic) Spatial Relations (2 static, 3 dynamic)
1. Locating self and other objects: Identifying the past or present position of objects in real space and on maps.
2. Alignment: Reasoning about spatial and temporal correspondence (Two important cases are scaling and the use of space as a proxy for time)
3. Perspective taking: Visualizing the appearance of a scene from a different vantage point.
4. Relations among objects, including self, in space: Visualizing the spatial relations defined by multiple locations (e.g,. distance between 2 points and angle formed by 3 points; important for making and using maps)

Figure 1 – Spatial Ability Types and Related Skills (Newcombe and Shipley 2013)

Newcombe's four categories of spatial abilities are intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic (Newcombe and Shipley 2013). The categories are based on the properties of an object or space on which the spatial ability acts, and whether or not those properties are changing. That is to say there is a distinction between intrinsic and extrinsic properties, and static and dynamic properties.

Intrinsic and extrinsic properties deal with the physical properties of the object or space. Intrinsic properties are those that belong to the object itself. They are the properties of an object that people use when determining what that object is. For example a rake is made up of a handle and its tines. The handle and tines and the way they go together to make a rake are intrinsic properties. You could go on to describe the intrinsic properties of the

handle itself indicating that which intrinsic properties are important to defining an object are relative to scale and perspective.

Extrinsic properties deal with an object's relationship to other objects in the world. When we say the coffee pot is next to the stove, we are describing an extrinsic property of the coffee pot (or the stove or both). What constitutes an extrinsic property is also subject to scale and perspective. For example, the coffee pot's GPS coordinates are an extrinsic property of the coffee pot with respect to the surface of the earth as viewed from space.

Static and dynamic properties deal with whether the intrinsic/extrinsic properties of an object are changing. Static properties are the properties of an object that remain constant, e.g. the relationship between a rake's handle and its tines. Dynamic properties deal with properties that change over time, whether it's a rake slowly revolving around an axis while floating in the void of space, or a car's relationship to the trees that line the road as it zips down the highway.

All of these frameworks have something to offer with respect to describing the field of spatial abilities and the research surrounding them, but because of their focus on spatial abilities, they fall short when used to describe broadly how people relate to space. Other research from psychology can add practice-based elements to the frameworks. Mohler has shown that students with high spatial ability scores more frequently work across views, double-check solutions, and deconstruct spatial problems (Mohler 2008). Researchers look at spatial ability in many different ways and create different functional divisions to support their research: scale (figural, vista, or environmental) (Hegarty et al. 2006), perspective (egocentric or allocentric) (Lozano, Hard, and Tversky 2007),

relationships (above, below, etc.) (Carlson and Kenny 2005), and intention (epistemic or pragmatic) (Antle and Wang 2013; Kirsh 1995).

Of all of these spatial ability classifications, the one that seems most appropriate to the critique of TEI systems is the one that lines up with the original presentation of tangible user interfaces – scale. People interact with things that are either graspable (figural scale), observable (vista scale), or traversable (environmental scale). Chapter 4 illustrates the utility of dividing TEI systems in this way, especially as it pertains to spatial cognition and embodiment and the framework presented in Chapter 5 uses the scale of interaction as a useful factor for narrowing down certain design decisions.

Evaluation

Since interfaces designed for spatial ability will need to be evaluated based on different metrics than traditional TEIs, we must develop a set of evaluation criteria specific to our goals. Possible evaluation metrics come from a number of pre-existing spatial ability tests and instruments, many of which are available from the Spatial Intelligence and Learning Center (SILC). Some examples include the Santa Barbara Sense of Direction Test (SBSOD), which correlates with heading-recall abilities (Burte and Hegarty 2012; Hegarty et al. 2002); The Santa Barbara Solids Test of imagining 2D cross-sections of 3D objects, which provides a more nuanced way to measure traditional mental rotation ability (Cohen and Hegarty 2007); and the two traditional mental rotation tests, Shepard and Metzler type mental rotation stimuli (Peters and Battista 2008) and Vandenberg and Kuse paper and pencil test (Peters et al. 1995), which have been used to assess spatial ability in the longitudinal studies described above. By drawing from the broad range of already available and validated metrics, we will be able to better understand the different

ways systems affect spatial ability within the context of the previous research we aim to extend.

CHAPTER 3
HOW SPACE AND THE BODY ARE RELATED

Introduction

Understanding the different ways the body and space relate provides the foundations of this design framework. Furthermore, these fields provide terminology that is useful for describing the design elements of interactive systems that engage spatial cognition. Evidence of the ways that we use our bodies in our interactions, perceptions and operations on space come from several different fields. Cognitive and neural sciences have found several specific examples of how our bodies relate to our perceptions of space, and how we mentally represent space and operate on those representations when navigating. Psychology, particularly developmental psychology, has provided a number of tests to quantify various spatial abilities.

Perception

The bulk of research relating the state of the body and how it relates to perceptions of space comes from psychology and cognitive sciences and provides many of the fundamental observations leading to the theory of embodied cognition. This research has shown that the motor system influences and underlies the perception of scale, distance, effort, and time. Time is noteworthy because there is recent evidence showing that there is a common representation in the brain for time, distance, and number, which implies a link towards the relationship between spatial ability and STEM fields (Casasanto, Fotakopoulou, and Boroditsky 2010).

Size

In this case, size refers to the apparent size of objects. Several studies have shown a link between the body and perceived size. First, there is evidence that the apparent size of objects is correlated with the ability to act on them. In one study, softball players were asked to select the size of a softball from one of several different sized black circles shortly after finishing a softball game. Players whose batting average was higher in the previous game tended to select a larger circle (Witt and Proffitt 2005). This observation links performance with perception, where performance is typically considered to rely on the capabilities of the body and mastery of a particular tool, e.g. a softball bat. While this research has its detractors (Firestone 2013), it does highlight a link that other researchers have backed up using technology.

By using head mounted stereoscopic displays and synchronous touches, van der Hoort et al. showed that it is possible to induce a body-swapping illusion with bodies that are very differently sized than our own (van der Hoort, Guterstam, and Ehrsson 2011). Specifically, they induced the perception that individuals' bodies were the size of Barbie dolls (30 cm tall) and giants (400 cm tall) by showing images of the doll's legs being stroked while simultaneously stroking the participant's legs. They then asked participants a series of questions to determine whether the illusion had worked and also about the apparent size and distance of objects in the view of the stereoscopic camera setup. People who perceived themselves to have tiny legs reported that the objects looked very large, while people given giant legs perceived objects to be very small.

Operating on scaled representations of objects (e.g. maps or architectural models) is a more traditional way to think of object size, but it is a skill that requires the use of a

number of different cognitive strategies. Changing the perceived size of the body to facilitate an altered perception of the size of real objects could be used as a tool to augment or induce comprehension of scales that are much different than our typical experience of them.

Distance

Distance is similar to size and related to the body in a similar way. Research has shown a link between the body and perceived distance by investigating tool appropriation and the effect of body size.

Early tool appropriation studies showed that monkey neurons that code for reachable space and typically fire only for stimuli on or very near the body begin to fire for stimuli on the end of a rake after the monkey has learned to use it to reach distant objects (Iriki, Tanaka, and Iwamura 1996). The fact that tools are similarly incorporated in to the body schema in humans has been shown by using response times to flashing light stimuli on the hand, on a tool and away from the body (Bonifazi et al. 2007). To establish the effect of tool appropriation on perceived distance, Witt conducted a study that asked participants to estimate the distance to a target in words and using a visual aide. First, participants sat along the edge of a table and for half of the trials held a vertical wooden handle and for the other half, a 39 cm baton. The handle was fixed in place, but the baton was movable. A light flashed somewhere on the table and then turned off. Participants were asked to either reach for the spot or estimate the distance to the spot. If they were asked to reach, they touched the table where the light had been, or if the light had been beyond their reach, they pointed to the spot. If they were asked to estimate, they gave a

verbal estimate in inches of the distance from the handle to where the point of light had

been. In a second study, when asked to estimate, participants moved two reference circles

so that they were the same distance from each other as the light had been from the handle.

The results of this study showed that participants estimated stimuli to be further away

when reaching with their hands than when reaching with a baton (Witt, Proffitt, and

Epstein 2005). In other words, using a tool for reaching distant objects shrinks perceived

distance, or distance perception is related to the capabilities of the body. The caveat here

is that the tool must actually be used in order to be incorporated in to the body schema

and influence perception of distance (Witt, Proffitt, and Epstein 2005; Maravita et al.

2002).

While Witt's study looks at near body distance estimation, the 2011 study by van der

Hoort showed a similar effect on larger distances. A smaller body perceives distances to

objects to be larger and vice versa (van der Hoort, Guterstam, and Ehrsson 2011).

Therefore, body capability can be augmented not only by tool use, but also by changing

the length of limbs, and both have similar effects on perceived distance. Digital media

and TEIs in particular are well suited to creating both effects and either can be used to

influence distance perception in the real world or in virtual environments.

Effort

A person's perception of the effort required to complete a task depends on the state and

capabilities of her body, and changes in perceived effort lead to altered estimations of

properties of space and objects, e.g. heaviness and steepness. While the effect of required

effort on perception does vary with ability and skill, e.g. wall height looks lower for

people who are good at climbing walls (Witt 2011; Taylor, Witt, and Sugovic 2011), this section focuses on the changes to perception based on the physical state of the body.

In 1999, Bhalla and Proffitt investigated the effect of wearing a heavy backpack, fatigue, low physical fitness, and old age and poor health on the perception of steepness (Bhalla and Proffitt 1999). In each case, people reported that hills appeared steeper than their more abled or less encumbered equivalents. In each case, participants were shown a hill either on a college campus or at a retirement home and were asked to judge its angle in three different ways: they verbally stated the angle of the hill in degrees; they rotated a disc so that it showed the angle of the hill in profile, and they set the angle of a plank on a tripod to the angle of the slope (Bhalla and Proffitt 1999). In the backpack case, 40 students wore a heavy backpack during the experiment and 90 students did not. Students wearing the backpack were first taken to a hill, given the backpack and asked to judge the angle. Students who did not wear the backpack were just asked to judge the angle. All students were also given an angle judgement test to determine how their general perception of angles matched with real angles. While all people tend to overestimate the angle of hills, students wearing the backpacks tended to overestimate the angles by more.

In 2003, Proffitt conducted a similar study looking at the effect of wearing a heavy backpack on distance estimates. Participants stood with their backs to a grassy field while a researcher placed a traffic cone at a particular distance along one of several radii. The participant then turned around and estimated the distance to the cone. Some participants wore a backpack that weighed one-fifth of their self-reported body weight. Other participants did not wear a backpack. Participants who wore the backpack consistently estimated the distance to the cones to be longer (Proffitt et al. 2003).

These examples provide evidence that our perception of the spatial qualities of an environment are linked to the capabilities and state of our bodies. While asking people to wear heavy backpacks while using a digital interface may not always be practical, the relationship between perception and state of body may be able to be exploited in other ways, for example by inducing identification with a virtual body with different capabilities, or by changing the qualities of a virtual environment to change perception of required effort.

Time

While time is not exactly a quality of space, the perception of time is related to the body and perception of space is related to perception of time. In fact, there is research showing a common representation in the brain for distance, time, and number (Casasanto, Fotakopoulou, and Boroditsky 2010) – another fact that may lead to insights on the link between spatial ability and STEM domains. However, perception of time is not necessarily influenced by movement. While physical elements of the environment may be altered to influence perception of time, it is important to note that not all cognition that is based on space can be influenced by movement or the state of the motor system more generally.

There is increasing evidence that understanding of time is based on metaphors built up through the direct experience of space. This claim is supported by studies that show that length and distance affect perceived time but that duration does not affect perceived distance (Casasanto, Fotakopoulou, and Boroditsky 2010; Boroditsky 2000). These findings show that space and time are "asymmetrically separable dimensions" where one

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dimension, time, relies more on the understanding of the other, space, than vice versa. This indicates that conception of time is based on conception space (Boroditsky 2000). This type of relationship between space and time helps explain examples from diverse fields including linguistics (space words used to describe temporal relationships, e.g. it will be a *long* time until I graduate) (Casasanto 2008a). However, a link between the two in the brain, does not necessarily link the two through the motor system. While the initial understanding of time may be scaffolded on the embodied experiences of space, there is evidence that thought, but not movement, affects perceptions of time in adults.

Of particular note in the case of the link between space and time are Boroditsky's experiments from 2002 (Boroditsky and Ramscar 2002). In the first study, participants filled out a questionnaire full of spatial primes and then were asked the question, "Next Wednesday's meeting has been moved forward two days. When is the meeting?" The question about the time of the meeting can be interpreted differently depending on how the participant perceives time. People tend to perceive time from either an "ego-moving" perspective, where they are moving forward through time or a "time-moving" perspective where time moves from the future towards them. The ego-moving perspective leads to "forward" meaning two days after Wednesday (Friday). The time-moving perspective changes the day to Monday, as time is moving from the future towards the present. Without any priming, people are equally likely to answer the question either way.

The spatial primes, shown in Figure 2 trigger the participant to think either of themselves moving or of things moving towards them. Depending on which prime participants received, they answered the question about Wednesday's meeting differently (Boroditsky and Ramscar 2002).

Figure 1a: Spatial prime used in Study 1.
Participants were given the following instructions
"Imagine you are the person in the picture. Notice there
is a chair on wheels, and a track. You are sitting in the
chair. While sitting in the chair, imagine how you
would manuever the chair to the X. Draw an arrow
indicating the path of motion."

Figure 1b: Spatial prime used in Study 1.
Participants were given the following instructions
"Imagine you are the person in the picture. Notice there
is a chair on wheels, and a track. You are holding a
rope attached to the chair. With the rope, imagine how
you would manuever the chair to the X. Draw an arrow
indicating the path of motion."

Figure 2 – Spatial priming from Boroditsky's
2002 study (Boroditsky and Ramscar 2002)

In a second study, Boroditsky asked people standing in line the question about

Wednesday's meeting. People near the front of the line, who had recently experienced

more forward motion, were more likely to answer the question as if they were moving

through time (Boroditsky and Ramscar 2002). In order to investigate the ability of

physical movement to prime particular perspective on time, Boroditsky set up an "office-

chair rodeo" outside the Stanford bookstore. Students either sat in an office chair and

moved towards the goal, or lassoed an office chair and pulled it towards themselves.

Immediately after completing the task, they answered the question about Wednesday's

meeting. The game they played had no effect on their answer (Boroditsky and Ramscar 2002).

Because of the role the body plays in our understanding of space, and because of the relationship between conceptions of space and other abstract concepts, like time, it is easy to leap to the conclusion that engaging the body will influence the higher level abstractions that derive from it. While it does not seem to be as simple as that, Boroditsky's work also shows that it may be possible to engage the body in ways that prime *thinking about space*, which does seem to influence the way people conceptualize time. Therefore, for designers, simply adding movement to an interface may not be enough to create a desired effect on cognition. It may be more important to design for a movement's effect on intention or thought if the designer's intention is to create a conceptual rather than perceptual effect.

Navigation

Navigation broadly deals with movement from one place to another in an environment. People employ many different strategies to accomplish navigation, and navigation can be performed in environments of varying scales: rooms, buildings, neighborhoods, cities, countries, planets, solar systems, galaxies, universes, etc. Navigation gets its own section here, because, in contrast to the spatial abilities described in the next section, it usually doesn't involve working with objects that are smaller than the body (Hegarty et al. 2006).

Given that navigation is so tightly related to our perception and construction of the world we inhabit, it seems important to first determine whether navigation, at an environmental scale, involves the same cognitive processes as the manipulation of objects at the figural

scale and whether large scale spatial cognition involves a single skill or several different skills (Hegarty et al. 2006). Several studies show that spatial abilities at different scales use different parts of the brain (Previc 1998) and that performance level on small scale operations is not associated with performance on environmental scale operations, except in a few cases (Allen et al. 1996). These findings lead to the hypothesis that there are one or more mediating skills that relate environmental scale navigation and figural scale object manipulations. In order to further investigate what skills people use to learn new environments, Hegarty conducted a study looking at the results of three different ways of learning an environment: physically moving through it, watching it on a video, or virtually moving through a virtual representation of it (Hegarty et al. 2006). The researchers recruited 236 participants from which 221 yielded usable results. All participants were given the following preliminary spatial ability assessments: (visual spatial abilities) Group Embedded Figures Test, Vandenburg Mental Rotations Test, Arrow Span Test, a perspective-taking ability test, (self-reported sense of direction) Santa Barbara Sense-of-Direction test, (verbal and reasoning abilities) Extended Range Vocabulary Test, Reading Span Test, and Abstract Reasoning Test. Participants then learned the environments in each of the three ways, in a controlled order. While the environments were necessarily different, researchers controlled aspects of them to make them as similar as possible, e.g. all paths followed straight lines and turns were all right angles.

In the real world environment case, participants were led along a route through two floors of a building on a college campus. After traversing the route once, the researcher led the participant through the route again while asking questions about it. At eight points along

the route the researcher asked the participant to estimate the straight-line distance and direction of two other points along the route. After completing the estimation tasks, participants drew a map of the route that included the eight landmarks.

In the virtual environment case, participants first practiced the controls on a square pathway that they were told was 100 feet long so that they could get a sense of movement and scale in the virtual space. They then traversed a path twice which contained four landmarks that were pointed out by the researcher. On the third traversal, the researcher asked them to stop at each landmark and estimate the distance and direction to two other points on the path. Afterwards, participants also drew a map of the environment including the landmarks.

In the video tape case, participants watched a video of walking through a building on a college campus, which showed seven landmarks along the route. Participants watched the video twice noting the location of the landmarks. On the third viewing, a researcher paused the video at each of the landmarks and asked the participants to judge the direction and distance to two other landmarks. Participants then drew a map of the environment showing the route and landmarks.

With respect to the performance on the measures of environmental learning, the method of exposure to the environment did not have a significant effect; however it did reveal significant individual differences, meaning that some people are better at learning and operating on environments than others. Correlating the results of the environmental learning tests with the other tests of spatial results revealed that people with high small-scale spatial ability scores (e.g. mental rotation) are better at learning environments from

visual information alone, the video and virtual environments cases, while people with high scores on the Santa Barbara Sense of Direction metric were better at learning environments from direct experience (Hegarty et al. 2006).

While learning of environments seems to be equivalent whether the environment is experienced directly or only viewed, the link between small-scale spatial skills and preference for visual presentation of information seems to bring questions of navigation back to issues of perception. If, as Proffitt suspects, the effect of the state of the body on perception provides some sort of evolutionary advantage, e.g. risk avoidance (Proffitt et al. 2003), then the role of the body in navigation may be that the body influences the perception of the environment to aide in navigation (Tversky 2002). For example, people judge buildings that are in perceptual groups, like cities, to be closer than they actually are, and they judge objects in different groups and the groups themselves to be farther apart than they actually are (Tversky 2002). These kinds of errors indicate a schematization of environmental knowledge that is useful in particular contexts, and that reduce the load related to operating on it in working memory and that can be more easily related to other spatial information obtained from other points of view across multiple senses (Tversky 2002). The perceptual systems that lead to these sorts of errors are the same perceptual systems that are involved in other spatial judgements that are also prone to perceptual errors (Tversky 2002; Proffitt et al. 2003).

Furthermore, navigation often occurs in a particular context, and that context provides affordances which support traversal of the environment and reduce or cancel out the effect of perceptual errors (Tversky 2002). In that case, navigation is an example of offloading cognition on to the environment (Clark 1997). In order for this sort of

offloading to work, the body's role in navigation must be understood as a perceptual system as much as a movement system. Given the results of Hegarty et al.'s study, visual perception is often enough to comprehend simple environments, but the role of additional senses in real world navigation is still unclear.

For designers of interactive systems interested in employing navigational elements, altering the perceived qualities of the environment may be a way to achieve a desired cognitive effect. This can be achieved in two primary ways, altering the ability of the body to act on the environment in a particular way, or altering the environment itself to highlight or hide elements related to its traversal.

Mental Representation (Spatial Abilities)

Spatial ability is defined as the ability to process and act on spatial information from the environment. Spatial information can be any number of things, from the geometry of an object, to the relationships like distance between two or more objects, to routes and landmarks as experienced during navigation (Denis and Loomis 2006). Early spatial ability research supposed that people were born with a certain level of spatial abilities that did not change over the course of their lives; however, recent research has shown that people develop spatial abilities with respect to experience and that interventions can be used to support and enhance people's spatial abilities (Mazalek et al. 2011; Quarles et al. 2008).

The relationship between spatial skills and the body extends to STEM learning. By comparing angular momentum test results between students who had experienced holding and moving a spinning bicycle wheel along the axes, Kontra et al. showed that physically

experiencing a phenomenon taught in physics classes can lead to better understanding of the concept, and, through the use of fMRI imaging showed that students who held the spinning wheel had greater activation of action planning and production regions of their brains when solving angular momentum problems (Kontra et al. 2015). The same study showed that the advantage of having held the bicycle wheel apparatus persisted over multiple days and led to higher quiz scores for problems relating to angular momentum and torque (Kontra et al. 2015). Another study showed that using gestures to explain a problem solving process leads to the creation of a mental representation of that problem solution (Trofatter et al. 2015). Researchers asked participants to solve the towers of Hanoi puzzle and then explain to another person how they solved it. Gesture, in this case, is contrasted with explaining the process while actually moving the discs used in the puzzle. Participants who gestured tended to improve their performance when solving the puzzle a second time, as long as the specific aspects puzzle remained the same (Trofatter et al. 2015). Because so many concepts in STEM education are related to physical qualities of systems, understanding the link between the body and spatial abilities can lead to new ways to promote the construction of mental representations about those concepts. Observations linking spatial abilities to embodied phenomena give reasons to believe that embodiment may be a good way to engage and support spatial abilities in both students with low spatial ability scores and for solving complex problems in STEM fields. Spatial skills related to mental rotation, scaling, and perspective taking provide evidence of this relationship.

Mental Rotation

Mental rotation is possibly the most studied spatial skill, and as such there are many

different tests to evaluate it. Mental rotation tests typically show a source image and

several target images. They then ask which target image is a rotated version of the source

image, or which of the target images shows the source image after applying a particular

rotation (Peters et al. 1995; Chandrasekharan, Athreya, and Srinivasan 2006).

Two of the most used mental rotation tests are the Cooper-Shepard mental rotation test

(Shepard and Cooper 1986) and the Vandenburg-Kuse mental rotation tests, shown in

Figure 3 (Peters et al. 1995). Variations of these tests have been developed to be used

with very young populations and to detect effects of neglect and other brain damage on

mental rotation ability.
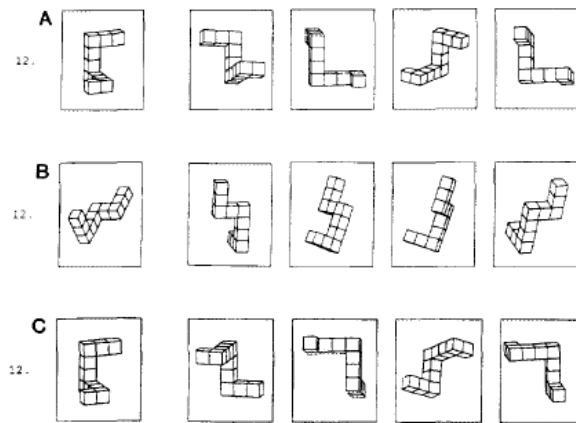
FIG. 1. Item 1 from set MRT(A) = top row, MRT(B) = middle row, and MRT(C) = bottom row. In each case, the stimulus on the left is the target. Subjects have to determine which two of the four sample stimuli on the right of the target are rotated versions of the target stimulus. There are 24 items in each test, and each item has two and only two correct matches. The fact that the targets in MRT(A) and MRT(C) are identical is coincidental; for other items all five stimuli may be different.

Figure 3 – Vandenburg and Kuse Mental
Rotation Stimuli (Peters et al. 1995)

Several examples of the link between the body and the execution of mental rotation tasks

look at the effect of congruent and incongruent actions on the response time to mental

rotation questions. Congruent actions are actions that correspond directly with the

rotation being applied to the source stimulus. Incongruent actions are actions that do not

relate or are the opposite of the rotation being applied to the source. Wexler used this

technique to show that when subjects perform congruent actions, they perform mental

rotations faster and more accurately than they would when sitting still, and when the

actions are incongruent, their performance in both speed and accuracy suffers (Wexler,

Kosslyn, and Berthoz 1998). In this study, participants rotated a joystick either clockwise

or counterclockwise at a particular speed. They were shown a source image with an

arrow pointing to it for several seconds and then were shown an arrow pointing to a

location somewhere else around a circle. After 1.5s, they were shown a target image at

the tip of the rotated arrow and asked whether it was a rotation or a rotation and

reflection. Figure 4 shows an example of this task.

| Phase 1 | Phase 2 | Phase 3 |
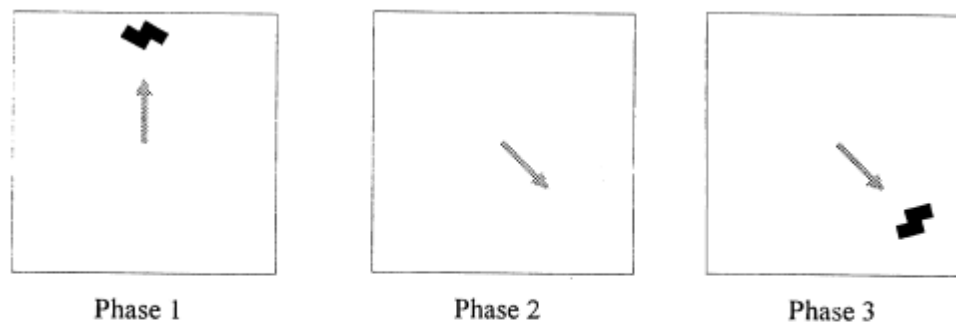
Fig. 2. A typical sequence of stimuli in the mental rotation task (the frame is not displayed, white and black are reversed, gray is yellow).

Figure 4 – Stimuli for testing effect of congruent and incongruent actions on mental rotation (Wexler, Kosslyn, and Berthoz 1998)

In 2001, Wohlschlaeger showed that planning a physical rotation influenced the response

times required for solving a mental rotation problem. In the first experiment, participants

were asked to plan a physical rotation of one of their hands in the direction of an arrow.

They were then asked to solve a mental rotation problem and complete the rotation of

their hand after solving the problem. Hand rotations about the same axis as the mental

rotation either shortened or lengthened the response time depending on whether the

rotations were congruent or incongruent. Hand rotations about axes that did not align

with the axis of the mental rotation stimulus had no effect on response time. This

experiment showed that there was a relationship between mental rotation and the motor

system; however participants offloaded some of the rotation planning by subtly moving

their hands in one direction or another. This meant that the experimenters could not

determine whether planning, preparing the rotation, or executing the rotation caused the

response time effect. A second experiment asked participants to either hold a knob in a

rotated position or keep two buttons pressed using index and middle fingers while solving

a mental rotation problem. The button condition kept participants from offloading the

planning of the rotation to their hands. The knob condition approximated the preparation

of a rotation movement. The button condition showed a similar effect on response times

as in the first experiment, but the knob condition had no effect. This experiment showed

that mental rotation and planning rotational movements are related and that movements

do not have to be executed to in order to influence mental rotation performance

(Wohlschläger 2001).

Chandrasekharan expanded on these results by investigating when people used gestures

to help solve mental rotation tasks and to what effect. In an initial experiment,

participants took a mental rotation test while researchers observed whether or not they

moved their hands or heads while solving the problems. For the group of participants

who did move their hands (17 out of 23 participants), most of the hand movements

corresponded with higher complexity trials. However, participants who did not use their hands tended to perform better on the tests. Since the researchers do not say whether participant's responses were more accurate when they used their hands, it is not clear whether the group who did not frequently use gestures was simply better at mental rotation to begin with. In a second experiment, one group of participants was forced to use gestures when solving the tasks while another group was asked to sit still. There was no significant difference between the two groups (Chandrasekharan, Athreya, and Srinivasan 2006).

As with the perception of time, there appears to be a strong link between the motor system and mental rotation, but the specifics of that relationship are still unclear. As with time and navigation, digital media can create altered experiences of space which may influence the cognitive skills which are built on them.

Scaling

Spatial scaling ability deals with the translation of information that has been represented at one scale to a different scale (Frick and Newcombe 2012). The most common example of the application of spatial scaling ability is map reading. A map is a representation of environmental information that has been symbolically abstracted and scaled to be comprehensible from a single point of view. In order to use the information the map provides, a map reader must be able to understand how it relates to the full size/real world objects and spaces that it represents.

Map reading, in particular, is a skill that is so widely applicable that some researchers have speculated that learning to read maps is important to the development of spatial

cognition, particularly related to understanding large scale spaces and how they relate to the body (Uttal 2000). However, reading maps requires the application of multiple cognitive skills, e.g. understanding correspondence between symbols and what they refer to (Liben and Downs 1994). Furthermore, reading maps requires the application of spatial scaling to several different elements of space: distance, shape, and heading. Therefore evaluating spatial scaling ability must move beyond asking children to extract and apply information contained in a map (Frick and Newcombe 2012).

Previous research has indicated that children develop symbol-referent recognition around age 3; they can locate items hidden in *unique* hiding places shown on maps, but they don't recognize spatial relationships between different symbols on maps until 4 years old. In order to investigate the development of spatial scaling skills, Frick and Newcombe designed an evaluation that focuses on scaling representations of distance and reduces the possibility of using other spatial skills to complete the task (Frick and Newcombe 2012).

> *Several task features were designed to reduce cognitive demands and thus investigate the developmental trajectory of spatial scaling ability independently from other skills necessary for map reading. First, the referent spaces and maps were aligned and in the same viewing angle, obviating the need for mental transformation (other than scaling) to compare them. Second, referent spaces and maps were both presented two-dimensionally, so no dimensional translation was required. Third, referent spaces and maps were presented simultaneously, obviating the need for memorization. Lastly, a placement method was used, based on findings (Huttenlocher et al., 2008) that*

The evaluation consists of several trials of three different stimuli shown in Figure 5: different green shapes representing grassy fields -- long and skinny (strip), rectangular, and circular including landmarks. The strip confined distance information to one dimension. The rectangular field constrains distance information to two dimensions, and the circular field added landmarks to investigate how they could be used as reference points.
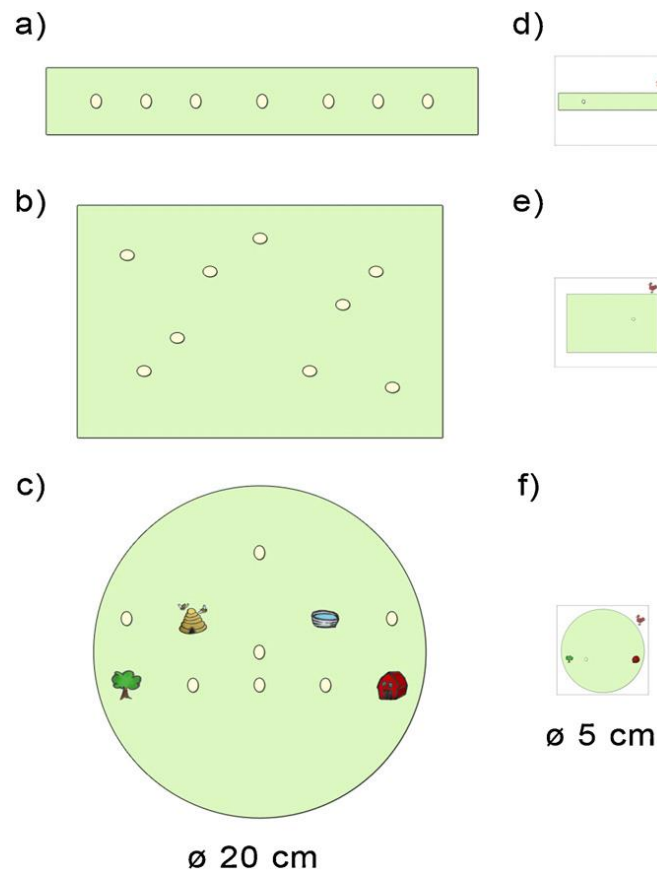
Figure 5 – Participants were shown the location of an egg on one of the small fields on the right and asked to place a rubber peg on one of the corresponding large fields on the left in the location corresponding to the egg on the small field. During the evaluation, the large maps were empty (or showed 2 of the four landmarks for the circular field), and the small maps showed one egg, a chicken and the two landmarks if applicable. The maps and fields used either a 1:1, 1:2, or 1:4 scale facto (Frick and Newcombe 2012).

The errors participants made in this test are more illuminating than the successes. Children aged three to four tended to choose locations that were closer to the center of the field, which is congruent with observations that young children perceive objects as discreet and total, while older children and adults placed objects closer to the edges, indicating that they performed some subdivision of the space and used the closest edges, instead of the center of the field, as a landmark (Piaget and Inhelder 1967; Frick and Newcombe 2012).

While the results of this study reveal the developmental sequence of scaling and some of the cognitive strategies children use to solve scaling problems, it does not reveal much about how the body relates to scaling ability. In fact, there are few studies that relate the body to scaling, particularly with its role in translating information from scaled representations to environmental spaces. While there are not specific studies, there is some evidence from the study of perception that the units used to scale objects and distances in an environment are derived from the body (Proffitt 2013; Proffitt and Linkenauger 2013). Profitt, in response to Firestone's criticism of theories of paternalistic vision illustrates that "people learn to interpret visual information by having agency in its creation" (Firestone 2013; Proffitt 2013). As people move, the visual information they perceive changes, and therefore their interpretation of visual information is tightly linked to their experiences of movement, or their ability to simulate movements in their motor systems. Furthermore, people learn to scale their visual perceptions based on their ability to act on objects or in environments. That scaling is also learned by actually acting (Proffitt 2013). Given that the scaling of visual information is based on movement, Profitt proposed that the units by which that information is scaled are related to the body,

specifically the body parts and movements that can be used to act on that visual information, e.g. objects that can be grasped are scaled using the size of the hand (Proffitt 2013).

While map reading is often concerned with translating inches to miles, the spatial scaling abilities described in the evaluation above deal much more directly with estimating relative distances. For example, in studies that ask children to find a toy in a sandbox in a location shown on a map (Huttenlocher, Newcombe, and Sandberg 1994), the children must scale the size of the representation of the toy and the size of the representation of the sandbox in order to make a correct placement. The units by which the map would be scaled would be hand size and distance covered when walking. While symbol/referent recognition might develop early, it may be that this embodied sense of scale requires more time and experience to apply to reading maps. For designers attempting to engage or support spatial scaling abilities, creating embodied ways to link the map scale to the ability to act on the objects and spaces represented by that map may be a good approach.

Perspective Taking

Perspective taking is broadly defined as, "… the ability to mentally represent a viewpoint different from one's own …" (Frick, Möhring, and Newcombe 2014). In this case, the mental representation is of the contents of a scene from a particular point of view. In spatial cognition, points of view are related to frames of reference and are, broadly, either egocentric or allocentric (Klatzky 1998). Egocentric points of view are those that correspond to the location of the body in space. Egocentric points of view define the spatial relationships objects using the body of the viewer as the primary reference point.

Allocentric points of view, on the other hand, are any point of view that is not from the location of the viewer's body (Klatzky 1998). In their paper, Frick et al. describe research that distinguishes between two types of allocentric perspective taking abilities. Level 1 abilities are present from birth and deal with what is seen by another observer. Level 1 abilities correspond to the knowledge that another person might see objects that are not visible from an egocentric perspective. Level 2 abilities deal with understanding exactly how a scene looks from a different perspective. Level 2 abilities only appear after around 4 years of age (Frick, Möhring, and Newcombe 2014).

The perspective-taking test described here was developed by Frick, Möhring, and Newcombe to research the development of perspective-taking abilities in 4 to 8 year olds. The research did not evaluate the malleability of perspective taking skills. Instead the researchers gave the test one time to a large group of children to determine the ways that perspective taking abilities change over the course of several years during childhood. They compared the answers from different age groups to determine the differences. The experiment does show that this test is useful for observing individual differences in perspective taking abilities and that it can be used to observe different approaches used to solve perspective taking problems between people with different level of perspective taking skills (Frick, Möhring, and Newcombe 2014).

The task designed by Frick, et al. is a picture selection task. It is based on a history of evaluations going back to Piaget's Three Mountains Task (Piaget and Inhelder 1967) and more recently a task designed by Hegarty and Waller to asses perspective taking in adults by selecting a photographer who could have taken a particular picture (Hegarty and Waller 2004). The picture selection task designed by Frick modified Hearty's test to be

appropriate for young children and to detect differences in perspective taking ability by four to eight year olds.

After a training task that uses physical objects and figures holding cameras to explain what exactly the experimenter was asking, participants moved on to the experimental task. In the first set of trials, participants are shown an image of a set of different shaped blocks arranged in a particular way with two photographer figures at 0, 90, or 180 degrees from the participant's perspective. They are then shown an image of the set of blocks and asked to say which photographer could have taken that picture. In the second set of trials, they are shown an image of the blocks with only one photographer. They are then shown a set of four photographs of the blocks and asked which photograph the photographer could have taken illustrated in Figure 6 (Frick, Möhring, and Newcombe 2014).

Figure 6 – Perspective Taking Task (Frick, Möhring, and Newcombe 2014)

Since this test was designed for children, and the level of success on this test plateaus after about 8 years of age, this test is not useful for assessing spatial skills in older people; however, it is useful for defining perspective taking and providing an example of a perspective taking task.

The role of the body in perspective taking is more clearly illustrated by experiments that look at answer biases for images that contain other bodies (Tversky and Hard 2009). Researchers showed participants one of the three photographs in Figure 7 and asked them where the book was:
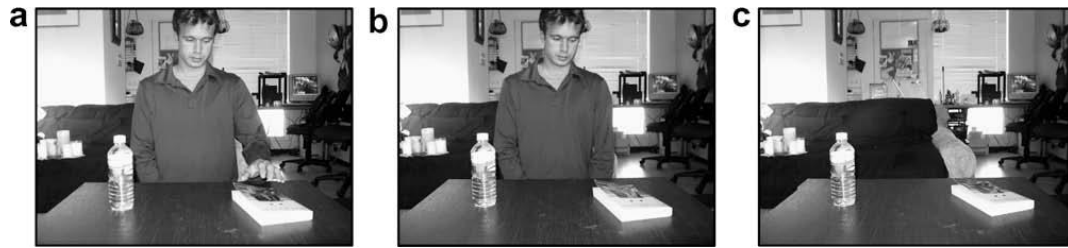
Figure 7 – Stimuli for perspective taking evaluation (Tversky and Hard 2009).

For images that showed another person, participants were much more likely to answer from the other person's perspective, i.e. say the book is on the left (Tversky and Hard 2009). In a second experiment, different participants were all shown the picture on the left of the person reaching for the book. Participants were asked one of four questions that emphasized action in different ways:

> *''In relation to the bottle, where does he place the book?'' (n = 39) and ''In relation to the bottle, where is the book placed?'' (n = 37). The other two questions implied no action: ''In relation to the bottle, where is his book?'' (n = 38) ''In relation to the bottle, where is the book?'' (n = 40) (Tversky and Hard 2009).*

Questions that mentioned action increased the frequency that a participant answered from the perspective of the person in the photograph. There are several possible reasons for these results that range from explicit attempts to communicate to the experimenter, language and behavior that mediates social interactions, and the activation of motor neurons involved in common coding of observed, imagined, and performed movements (Tversky and Hard 2009).

These experiments illustrate how perspective taking is applied in different situations and hint at the role of the body in its use. For designers looking to engage perspective taking

ability, action may be important for inducing users to interact with an environment from a different point of view, and including another body in the scene might aide them in solving perspective taking problems.

Conclusion

By looking at all of these different types of spatial perception, cognition and abilities together, we can begin to concretize the elements of embodiment that influence how we engage with space. Given the results of the research discussed above, it seems that the most direct link between spatial cognition and the body comes from altered perception related to the body's ability to act on the environment. While other more abstract spatial skills are embodied, in that they use the motor system as a foundation, they may be dissociated from the actual state of the motor system at the moment of their use. It is therefore worth knowing how they relate to the motor system, but it may not be sufficient to design interactions that require particular movements to support those skills. Designers need to relate movements to feedback or outputs in ways that influence perception and ability and create new relationships between the body and space in order to influence higher level spatial skills.

By designing interfaces that alter ability in systematic ways with the intention of influencing spatial perception as a way to affect higher level spatial abilities, we may be able to begin to influence spatial skills in ways that have yet to be shown to be possible. The case study of emBodied Digital Creativity, described in a Chapter 6, is one example of how this might be possible. The case study of TASC illustrates one possible design process that accomplishes this goal. But first, we have to look at how tangible and

embodied interfaces engage the body, so that it is clear what spatial skills and perceptions

they are most suited for influencing and how.

CHAPTER 4
HOW TEIS BRING BODY AND SPACE TOGETHER

Introduction

In order to link embodied interactions with space, it is useful to first classify interactions

with digital media from a spatial perspective. As discussed in the introduction, most

frameworks created to describe TEIs work on a very high level, even when focusing on

the way they relate to the body (Fernaeus, Tholander, and Jonsson 2008b; van Dijk, van

der Lugt, and Hummels 2013). It is the goal of this chapter to describe the interactions

with several systems at a fine enough level so it is clear how what the interactor is doing

relates to space, particularly from a perceptual perspective. Because space is the primary

focus of this analysis, examples have been chosen that are noteworthy from that point of

view. Therefore, some examples engage the body in more limited ways than others, but

still alter the space-body relationship in noteworthy ways.

Furthermore, this focus on space requires a spatial classification, as opposed to a

classification that focuses on application or movement type or type of embodiment.

However, as will be shown, a spatial classification actually incorporates many of those

elements in to it. While there are several available ways to classify space and the ways

our bodies relate to it, many of them fall short when trying to use them to link qualities of

interactions to our bodies and to space. Wai proposed a framework for mental rotation

that includes 2D visualization, 3D visualization, mechanical reasoning and abstract

reasoning (Wai, Lubinski, and Benbow 2009). As should be clear at this point, this

classification only applies to a single skill, mental rotation, and while these classifications

show that mental rotation ability can be applied across a very broad range of spatial tasks,

the categories simply are not broad enough to be meaningful for the relationship between the body and space that TEIs create.

While frameworks developed by Wai and others often attempt to describe the spatial qualities of the task or the environment, none of them are intrinsically body-based. In that regard, only scale relates the environment to the body in terms of the body's ability to act. Spatial cognition research describes three major scales, one of which is broken down even further. The space that the body can directly act on is called the figural scale. Beyond that, space that can be seen from a single point of view, but not manipulated is called the vista scale. Space that must be moved through in order to be fully comprehended is the environmental scale (Hegarty et al. 2006; Montello 1993). Figural scale, in perception research is broken down further in to personal, and peripersonal. Personal space is the space actually occupied by the body. Peripersonal space is very near the body, in such a way that it can be processed in the same way as personal space (Vaishnavi, Calhoun, and Chatterjee 2001).

By describing interactions with digital media systems in terms of scale, and describing how systems that work at those scales can alter the perceptual experiences of those spaces, we can begin to unravel how digital media, embodied interaction, and space can work together to reinforce or alter spatial cognition.

Figural

Figural is the most common scale digital media systems work within. It is the realm of most screen-based media, clicking and dragging, touch screens and tabletop computing. Each of these puts the content/objects of interaction within reach of the interactor. There

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are some interesting disconnects between digital media that operates at the figural scale

and the real world figural scale, but whether or not we perceive them as essentially

different is unclear. For example, clicking and dragging a window on the screen separates

the kinesthetic qualities of holding the mouse from the perceptual qualities of the

movement of the window, but it links them back again through direct manipulation which

creates a one-to-one relationship between the two movements. This is one of the

perceptual disconnects that embodied interactions can reconcile, but it is not the only way

that digital media influences spatial perception on a figural scale.

FoldIt

FoldIT, Figure 8, is a game that shows players a 3D model of a protein molecule and asks

them to rotate different parts of it to achieve the correct shape (Cooper et al. 2010). The

shape of proteins is important because it determines how they interact and combine with

other molecules and is what ultimately makes them valuable as building blocks of life.

However, there is no way to directly see how the molecular bonds in a protein molecule

dictate the protein's shape, and scientists have yet to figure out an indirect way to

determine the internal structure of proteins.

Figure 8– Foldit http://fold.it/portal/info/science
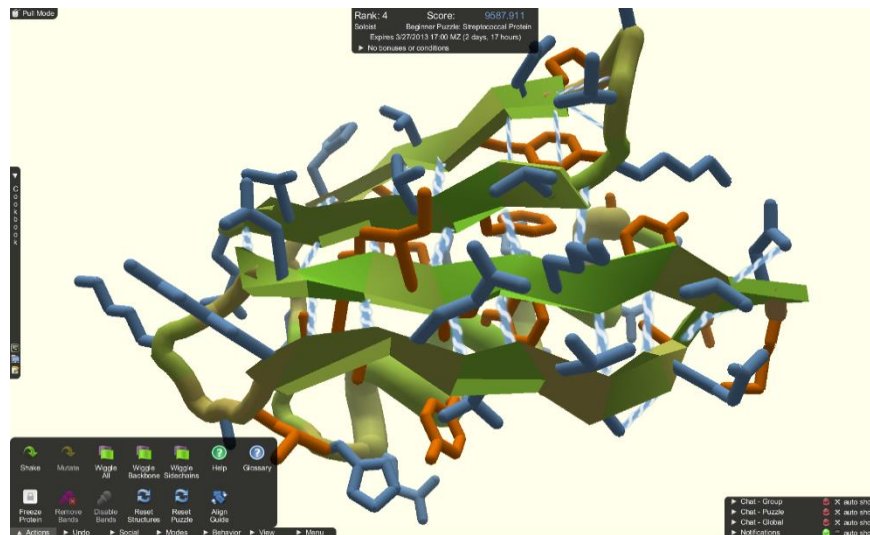
In FoldIT, users use a mouse and keyboard to manipulate the orientation of different parts

of a protein molecule. While this interaction does not engage the body in ways typically

associated with TEIs, the fact that players have been able to successfully determine the

correct positions of parts of the molecules using this interface indicates that the spatial

skills they are using in the real world are applicable in this interface. That is to say that

the 3D visual representation, the way it visualizes the angles and the molecular structures,

and players' familiarity with the keyboard/mouse interface is sufficient for players to engage with the molecule, to some degree, as if it were actually present on their desks.

In order to figure out the correct rotations to apply to the molecules, players first learn to see the protein as a collection of smaller parts and to realize that the shape of the protein is determined by the collective positions of those parts. Next they learn to visualize how changing one part will affect the rest of the molecule and to build up sequences of steps that will lead to the desired shape. By creating this interactive visualization of protein structures, the game designers created a way for players to apply spatial skills that would normally be used on objects at the figural scale to an object that cannot typically be touched, or seen because of its small size. Therefore, one way digital media alters the qualities of space is by changing the apparent size of an object and the scope of its internal qualities, making it able to be manipulated by a human body in ways it would not be in the natural environment.

URP

The alteration of scale of an object works in both directions. URP, Figure 9, creates a tabletop scale representation of an urban environment including buildings, sun light, and wind vectors. URP is a multitouch and object based tabletop urban planning simulation. In one of the applications that run on it, users place physical models of buildings on the surface of the table to observe the effect their position and orientation has on a wind vector simulation projected on the table's surface (Underkoffler and Ishii 1999).
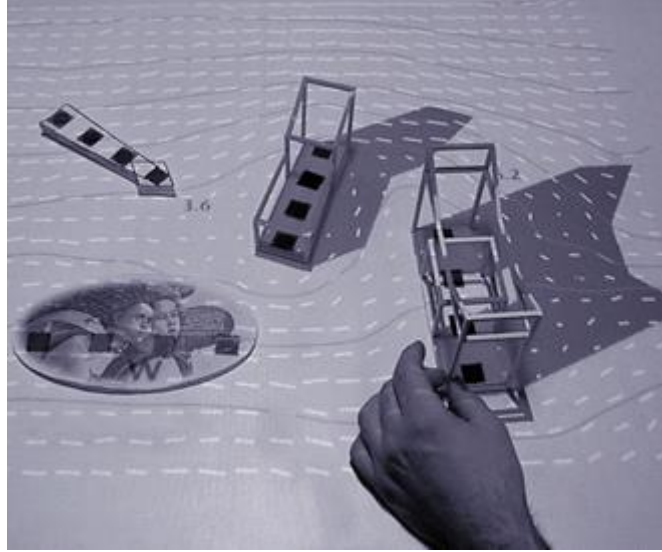
Figure 9 – URP (Underkoffler and Ishii 1999)

URP, however, does more than just scale a city block down. It also provides physical objects that interactors move, instead of using a mouse to click and drag them around on a remote screen. It couples the interaction of moving the building objects with real time feedback in the same interface, by changing the projected wind vectors to represent the time of day and the effect of the building positions.

Physical movement of objects has been shown to have cognitive benefits over touchscreen and mouse/keyboard based interactions for the same tasks (Antle and Wang 2013). Therefore URP uses digital media to support spatial skills in two primary ways. First, like FoldIt, it creates a version of the system that can be interacted with at the figural scale using already present spatial skills. Second, it engages the motor system directly giving a kinesthetic experience to the interaction that can serve to support future inferences about similar systems.

Topobo

While Topobo does not alter the scale of anything in particular, it couples the interaction and output in a completely physical system, which gives interactors a way to explore properties of the physical world, like gravity and balance, as different qualities of the system change over time. Topobo, Figure 10, is a construction kit made up of passive and active components that are snapped together to build moving sculptures. The passive components are typical ball-and-socket type building blocks. The active components have motors in them that can remember movements that they are caused to make and play them back. With these blocks, a person can build walking animal sculptures, or other figures that move on their own (Raffle, Parkes, and Ishii 2004).

Figure 10 – Topobo http://www.topobo.com/
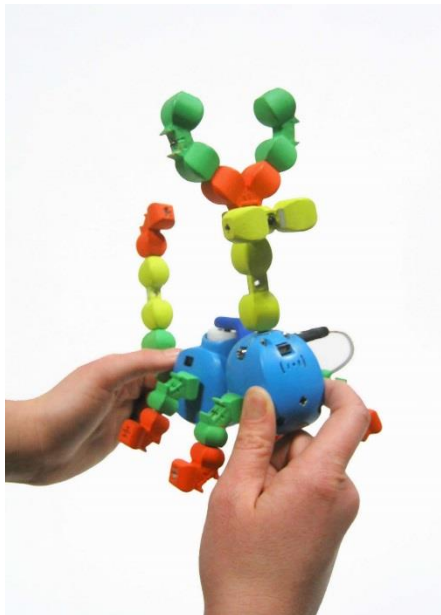
There are two main spatial interactions with Topobo, each of which engages a different spatial skill. First, people use the blocks to construct an animal. Construction, assembly, and block play all rely on skills that relate individual parts to whole objects. Each component block of the Topobo kit can be used to create a different type of spatial

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relationship between the blocks that it connects. By understanding the different

relationships each block creates and using those relationships to build a particular

sculpture that can exhibit the desired behaviors, an interactor can develop a physical

sense of the way the parts of the system relate to its overall structure and ultimately to its

behavior.

The second type of interaction Topobo supports is animating the sculpture to walk,

dance, wag its tail, etc. To animate a sculpture, players rotate the components that are

connected to the active components. The sculpture then repeats those rotations over and

over again. By rotating the four legs and the two body segments of the sculpture in Figure

10, for example, a player can make the dragon-thing walk. However, only certain sets of

movements lead to walking. Other sets of movements might make it trip on its own feet

and fall over. By exploring the different sets of individual movements that lead to a

desired total movement, interactors can get a sense of how each part of that particular

sculpture affects properties of a dynamic system. The incorporation of physical

manipulation in to this type of system gives interactors a way to relate the different

qualities of the movement of the sculpture to their physical manipulations of it. For

example, if rotating one body segment too far in one direction leads to an unstable

system, interactors will have a physical sense that they can associate with what too far

actually is.

Topobo uses the digital medium to create a system that enables interactors to work with

objects at the figural scale that can create an embodied link to the perception of the

behaviors of dynamic systems as they change over time and relates that back to the

relationships between the components those systems are built from.

Qualities of figural scale digital media

Based on the systems described above, digital and embodied media at a figural scale engages spatial cognition in two main ways: scaling large or small objects to be engaged with on a figural level and providing a kinesthetic experience that relates to properties of the system.

Vista

Interactive systems that operate at the vista scale are few and far between, and there are especially few (none to my knowledge) that use interaction to engage particular aspects of spatial cognition. There are interfaces that enable operating on digital content at a distance, and there are digital systems that alter the way vista scale space is perceived, but none that do both at the same time to create an embodied relationship to vista scale spatial information. Because vista scale spatial cognition relies so heavily on visual perception, visual illusions are a strong starting point for understanding how digital media might engage spatial cognition at a vista scale. The Mystery Spot near Santa Cruz, California, and projection mapping installations provide examples of how these visual illusions can influence cognition of space. Embodied interactions with vista scale spaces can be based on traditional skills that enable people to engage with objects at a distance, such as throwing objects. SMSlingshot provides an example of the use of digital media to support that sort of interaction.

Mystery Spot

The Mystery Spot is a tourist attraction outside of Santa Cruz, California, which, through clever engineering and its construction on the side of a moderately steep hill, tricks

visitors in to perceiving supposedly impossible events, such as water flowing uphill and short people appearing taller than tall people. The main attraction at The Mystery Spot is a cabin inside of which people appear to stand on the walls, apparently perpendicular to the pull of gravity.

Figure 11 – The Mystery Spot makes vertical feel crooked.

While the guides at The Mystery Spot claim that there is a gravitational anomaly that causes the behaviors, the illusion is actually created by building the cabin at an angle and blocking out visual information that would make it obvious that the floor of the cabin is tilted along the hill. The construction of The Mystery Spot breaks the link between the proprioceptive and vestibular sensations of standing vertically and the visual perception of objects that are expected to be vertical and horizontal.

Digital media can employ the architectural techniques of The Mystery Spot without having to actually build cabins on hillside by creating virtual spaces in which the visual

feedback does not match the proprioceptive sensations of the body. This possibility

becomes especially powerful in virtual reality environments that combine visual and

proprioceptive feedback while blocking out other external information that could break

the illusion.

Projection Mapping

Projection mapping aligns ultra-bright, high-resolution projected images with the

physical features of objects and environments. By combining projection mapping with

3D graphics, objects and spaces can appear to have spatial properties and relationships

that are not necessarily defined by their physical aspects. Projection mapping installations

range in scale from sculptural (projecting on to piles of objects like boxes) to

architectural (projecting on to the features of buildings). The architectural scale

projections clearly highlight the possibilities for altering spatial features. In 2010, artist

Dan Gregor and his collaborators displayed a projection mapped animation on the

Astronomical Clock Tower in Prague to celebrate the 600 year anniversary of its

construction ("TheMacula - The 600 Years, Astronomical Clock Tower, Prague" 2016).

The animation depicts the history of Prague through the life of the clock tower and

manipulates the visible qualities of the projection to show the destruction of the tower, its

rebuilding, and to make it appear that the clockworks are visible from the outside of the

tower.

Figure 12 – Frames from The Macula. The left shows a projection highlighting the physical features of the clock tower, giving them an unnatural appearance of depth. The middle image shows the projection being used to show the internal mechanisms of the tower, and the right image shows a projection that changes the contours of the surface of the tower ("TheMacula - The 600 Years, Astronomical Clock Tower, Prague" 2016).

The clock tower project shows how projection mapping can alter the apparent spatial qualities of architectural objects. A similar project from Sony shows the possibilities of using projection mapping in an indoor space. In this project a living room is transformed to a holodeck where a man on a couch uses his laser eyes to explode floating fruit ("Sony Realtime Projection Mapping 1 on Vimeo" 2016). The images below show how simply projecting images in ways that highlight, hide, and alter the features of the room can make the space of the room feel completely different.
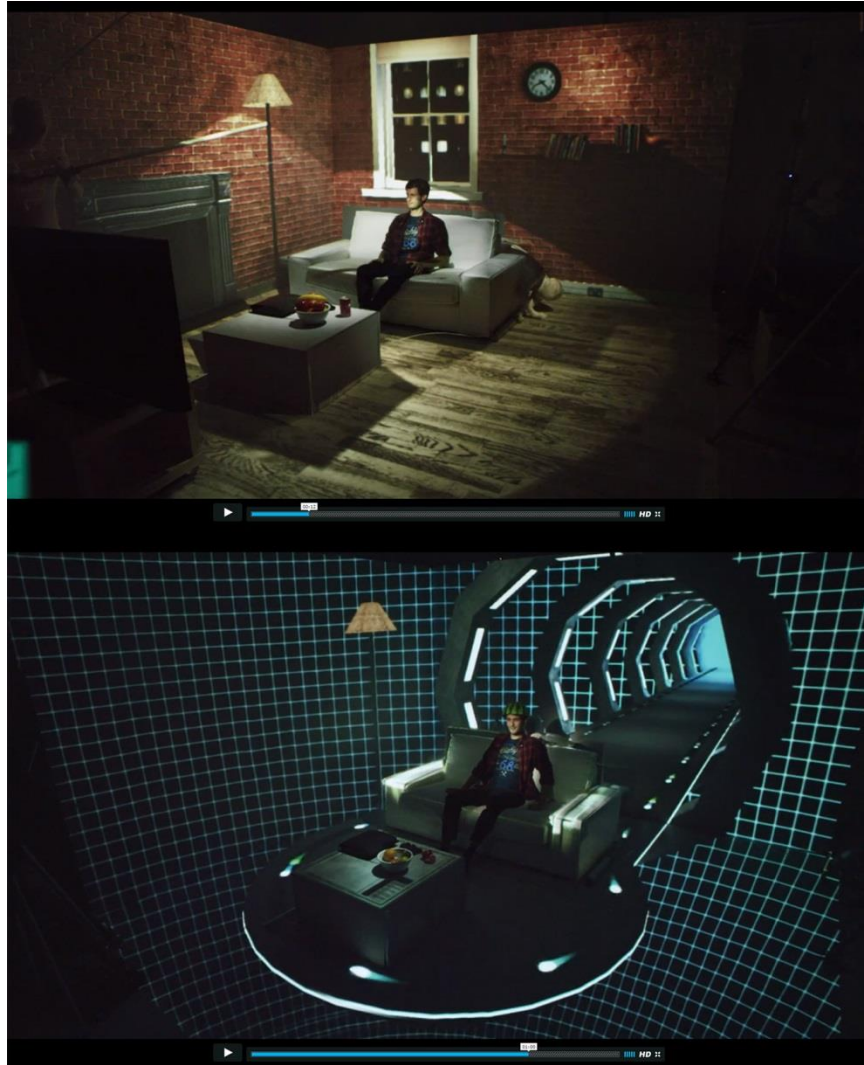
Figure 13 – Two scenes from the Sony projection mapping demo. Both scenes are shot in the same studio space with blank walls and minimal furniture. Projection is used to significantly change the apparent properties of the room ("Sony Realtime Projection Mapping 1 on Vimeo" 2016).

The examples above are not interactive. Interactive projection mapping installations have been slow to emerge due to complexities involved in tracking objects as they move and updating the mapping to reflect that movement. As object tracking technology and processing power improve, installations that alter projections based on user input will become more common. Ping Pong Plus is one early example of tracking objects and altering projections based on their movement (Ishii et al. 1999). In one game, holes

appear in the ping pong table wherever the balls bounces. Players lose the point if the ball

hits an empty square (Ishii et al. 1999).
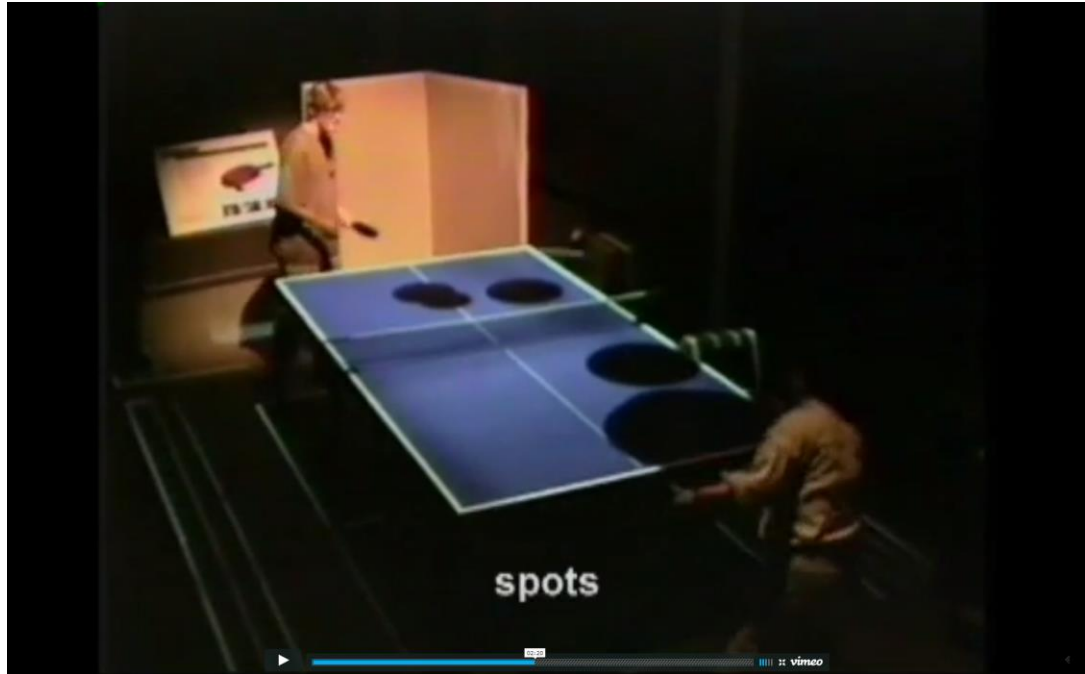
Figure 14 – Holes appear where the ball has contacted the table ("PingPongPlus CHI
Video 1999 on Vimeo" 2016).

More recently, tracking technology has made it possible to track facial movements and

map projections on to facial features, which can create eerie illusions of the contents of

the inside of a head, or be used for high-tech makeup with depth and volume (Landau

2016).
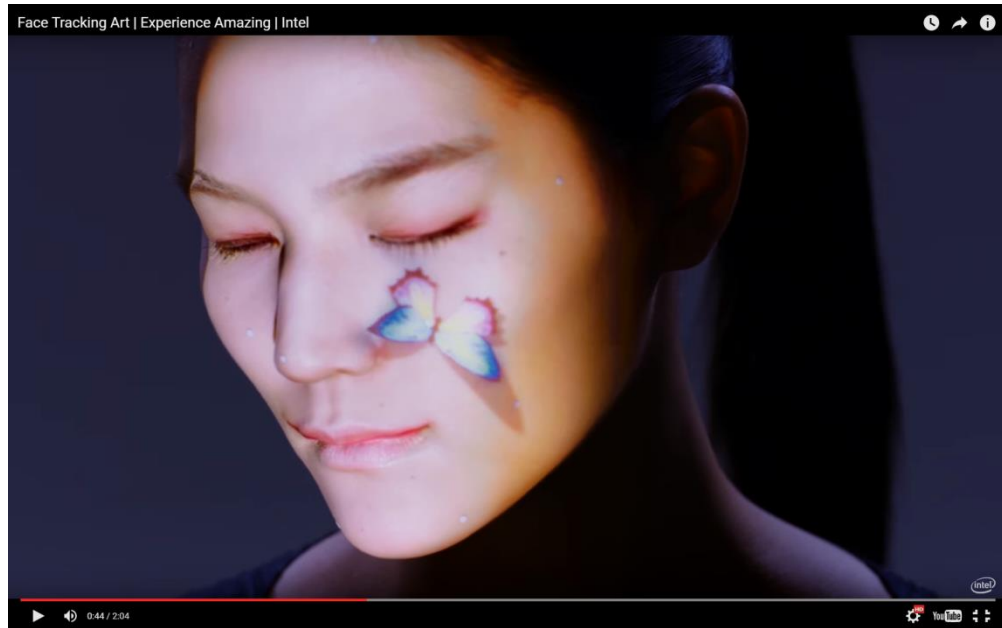
Figure 15 – A projected butterfly casts a shadow on a models face. The video shows the butterfly landing and then staying in the same position on the model's face when she moves her head (Landau 2016).

Because cognition of space at the vista scale is so strongly linked with visual perception, the combination of projection mapping and 3D computer graphics can be a powerful way to alter people's relationships with spaces that they can observe. While making those spaces respond to their bodies in ways that lead to alterations of spatial cognition is still a complicated technological problem, the examples above illustrate some of the possibilities. How people will interact with these responsive spaces is still unclear. SMSlingshot illustrates one method that could be used for giving users some agency in projection mapped spaces.

SMSlingShot

SMSlingshot does not necessarily engage vista scale spatial cognition in a particularly novel way, but it does provide an example of how embodied interaction can be employed to engage with vista scale space. As an attempt to give citizens some agency of the

increasingly advertising focused digital content in urban environments, the VR/Urban

collective designed and developed a slingshot interface that shoots projected text

messages on to the sides of buildings (Fischer, Hornecker, and Zoellner 2013).

Figure 16 – Users key a message using the keypad then aim and fire the slingshot at the wall. (Fischer, Hornecker, and Zoellner 2013).

Users key a message in to the slingshot using a standard cell phone keypad. When they

pull back the band, the slingshot shines a green laser on the building's façade. A camera

tracks the green dot and when the band is released, a projector shines the message at the

location of the dot.

Figure 17 – A projector displays the message at the appropriate spot (Fischer, Hornecker, and Zoellner 2013).

Interacting with the vista scale environment is, by definition, interaction at distance and has always required spatial skills to achieve desired results. Throwing a ball at a pyramid of milk bottles, for example, requires an understanding of force and motion, how to use the body to impart that force and motion, and how much force is required to knock the bottle down. Translating these sorts of actions in to embodied interfaces for use with digital content is one possible approach for designing interactions that alter vista scale spatial cognition.

Environmental

The use of digital media at the environmental scale has become more and more possible as mobile computing has become more and more mainstream. However, moving around and seeing a dot move on a map is not nearly the first time digital media has explored the possibilities of engaging spatial perception on an environmental scale. Virtual environments have worked with environmental scale information for decades and have

altered qualities of those environments in lots of fantastic ways; however, there is

evidence that these virtual environments, when explored using a keyboard and mouse,

may not be perceived in the same ways as real world environments (Darken et al. 1999).

While virtual environments may not necessarily engage the perceptual system in the same

ways, their design does point to ways that digital media can alter environments. Creating

embodied interactions that couple the environmental alterations seen in virtual

environments with kinesthetic experiences may lead to designs that support or alter

spatial skills. Therefore, this section describes both screen based virtual environments

and embodied media that works on an environmental scale.

Slower Speed of Light

A Slower Speed of Light, Figure 18, is a game played in a virtual 3D environment from a first-person perspective, like *Doom* or *Fallout* (Kortemeyer, Tan, and Schirra 2013). Players control movement through the virtual environment using a keyboard and mouse. While keyboard and mouse based systems are not typically included in discussions of embodied interactions, there is some evidence that movement in virtual worlds, regardless of the interface, makes it possible for people to apply som of the same spatial skills as physical movement. In particular, embodied elements of virtual space have similar effects on descriptions of time as real space (Mylov 2002).
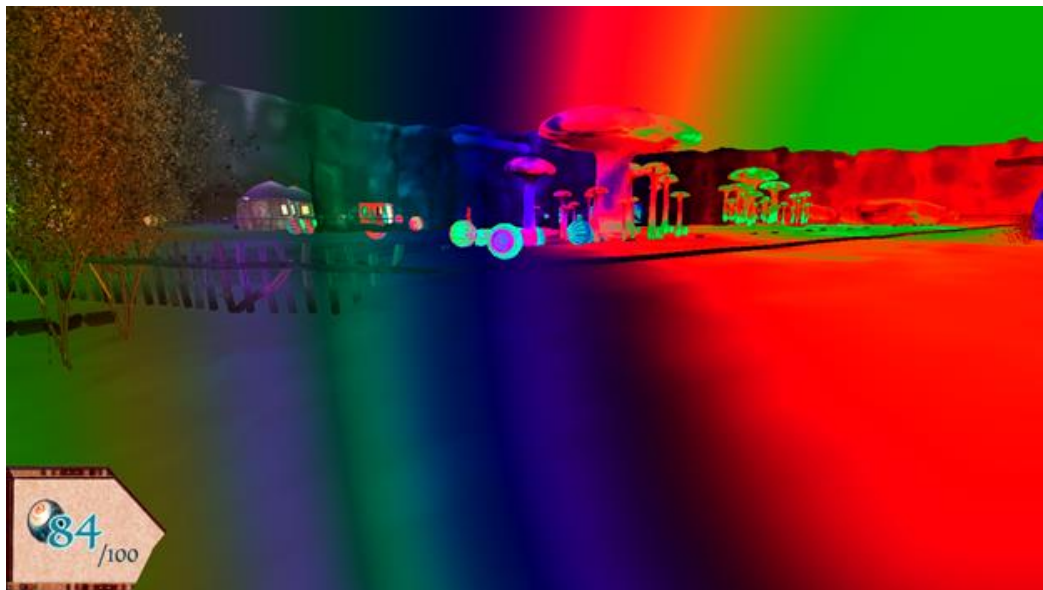
Figure 18 – A Slower Speed of Light

As players collect tokens, the speed of light in the virtual world slows down. Initially this affects the appearance of objects in the game, by changing colors due to the Doppler effect. As the speed of light approaches the speed of movement, relativistic effects become apparent. The important thing to emphasize here is that the player's (virtual) body and how it moves in the environment are not changing. The underlying physical

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properties of the environment are what changes, so that when the player moves, his

perceptual experience of moving changes. This may be a fundamental key to

understanding how to design interactive systems that actually affect spatial cognition that

underlies spatial skills. In the real world, our physical abilities can only change a small

amount relative to the scope of the world, so in order to alter perceptions of space, it may

be more successful to use digital media to alter the qualities of the environments (like

maps do) than to alter a body's ability to act on it.

While maps, and URP and FoldIt do alter the environment, they do so by bringing the

objects and spaces nearer to us, to be interacted with at a figural scale. *A Slower Speed of*

Light alters an environment in a way that must be navigated to be experienced, showing

how digital media can alter fundamental physical properties of space to great effect.

feelSpace

feelSpace, Figure 19, is a belt with several vibrating motors sewn along its length. The

motor that is facing north vibrates, so that the person wearing the belt always has a

physical sensation related to magnetic north (Nagel et al. 2005).

Figure 19 – feelSpace

To interact with this system, a person wears the belt and walks around. The designers of

the belt asked people to wear it for six weeks or more. Over the course of the trials,

participants stopped being aware of the vibrations, but also experienced an enhanced sense of direction. Many people reported feeling like they had a better idea of how to get from one place to another. At the end of the test, the researchers led blindfolded participants around a path and then asked them to walk it again by themselves. Most of them followed the path successfully.

While feelSpace does not alter the environment, it does directly alter the wearer's perception of the environment. Over time, as with age, fitness and health, feelSpace begins to create a new sense of ability in the world. This ability to act on the world (or the perception of the environment's response to the presence of the body) is what appears to underlie spatial ability. By coupling embodied interactions that create new abilities with digital media's ability to alter the qualities of space that those abilities can act within, embodied media begins to reveal its potential for engaging spatial cognition in fundamentally new ways.

Conclusion

The examples discussed above illustrate that, regardless of the scale at which they operate, digital and embodied media do two main things with respect to spatial cognition: alter the qualities of an environment and alter our perception of an environment. Altering the qualities of the environment can make it possible for people to engage with content using spatial abilities that would normally not be available. Altering the perception of an environment can give people new ways to relate their embodied experience to the qualities of space.

This analysis begins to make clear that the type of interaction and the way an interface relates to space are somewhat independent of each other. That is to say that a digital media interface can alter space in the same way for many different types of interactions, and that different types of interactions can lead to the same effect on perceptions of the environment. Therefore, from a design point of view, it becomes very important to keep in mind the goals of the system as they relate to spatial perception in order to select a good combination of interaction and spatial effect. The next chapter covers the relationship between cognitive effects and embodied interaction by bringing the analyses from the previous chapters together in to a single set of guidelines for designing embodied interactive systems that engage, support or alter spatial cognition.

CHAPTER 5
DESIGNING INTERACTIONS THAT ENGAGE SPATIAL COGNITION

The design framework presented in this chapter is useful for three primary tasks: defining a design space that encompasses systems the leverage embodiment to engage spatial cognition, designing interactions that establish embodiment based on aspects of embodied cognition, and designing interventions that engage one or more aspects of spatial cognition.

Design Space

Not all TEIs incorporate the body or present media in a way that meaningfully engages spatial cognition. Through the critique of TEI systems presented in the previous chapter, I established elements of interactive systems that engage the body and related that engagement to spatial cognition. Those systems constitute specific examples of TEIs that fall within the design space of this framework. My analysis of them describes how they fit in that design space, which leads to their placement within the table in Figure 20.

Aspects of Spatial Cognition

Embodiment		Mental Rotation	Scaling	Force & Motion	Assembly	Perspective	Effort	Size	Distance	Time	Distance	Survey/Route	Heading	Intervention
		Abilities					Perception				Navigation			
Figural	Point and click	FoldIT	FoldIT											Manipulate virtual 3D object
Figural	Move physical objects on table	URP	URP											Change Simulation
Figural	Combine blocks and move them			Topobo	Topobo									Build and animate animal
Vista	Hit ball						Ping Pong Plus	Ping Pong Plus						Change apparent spatial properties of table
Vista	Aim and shoot slingshot							SMSlingshot	SMSlingshot					Show messages on walls
Vista	N/A						Projection Mapping	Projection Mapping						Change apparent spatial properties of objects
Environmental	Arrow keys								Slower Speed of Light	Slower Speed of Light	Slower Speed of Light			Appearance of environment changes based on light speed
Environmental	Walk around											feelSpace	feelSpace	Feel vibrations on part of body oriented towards north

Figure 20 – Illustration of the design space for TEIs that engage spatial cognition

Altogether, the interfaces, their interaction methods and their relationships to spatial cognition, lead to the following definition of the design space they encompass:

> **The design space of this framework can be defined as digital systems that, through a combination of embodiment and intervention, engage, support, or alter some aspect of spatial cognition.**

This definition and the table illustrating it can give designers a good idea about whether their projects are good candidates for the use of this framework. It can also provide a starting point for their designs, by showing which combinations of interactions, outputs, and spatial cognition effects are well suited to each other. The following sections define the embodiment, intervention and aspects of spatial cognition axes of the diagram in

detail and discuss trends and opportunities for design highlighted by plotting systems within the design space.

Embodiment

The embodiment axis describes the ways that TEIs engage the body from a physical point of view. The descriptions of the embodied aspects of the systems are the physical actions an interactor takes when engaging with the system.
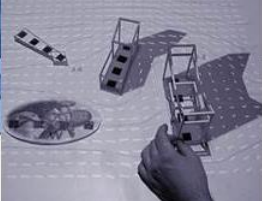
Figure 21 – The embodiment axis and an example interface for each scale.

The ways that interfaces establish embodiment can be classified by scale as described in Chapter 4 and based on definitions drawn from Montello (1993). The scales; figural, vista, and environmental; broadly describe the ways that people interact with objects and

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spaces in the physical world, and TEIs have been designed that engage the body at each of these scales. Figural scale modes of embodiment provide physical objects that can be grasped and moved, e.g. tangible objects on an interactive surface. Vista scale modes of embodiment provide ways that people can interact with objects and spaces that are beyond reach, like shooting a slingshot at a distant wall. Environmental scale modes of embodiment require users to walk around an environment to interact with the system. For example, the orientation of the vibrations in the feelSpace belt change as a user navigates on a day to day basis.

The specific techniques that interfaces use to engage the body are described in the second column. These are abstract descriptions of the physical actions a user takes when interacting with the system. The descriptions are drawn from my own analysis of existing TEIs. While some modes of embodiment, like point and click and hit ball, can support action at multiple scales, others, like move physical objects on tabletop are inherently linked to a single scale. For modes of embodiment that can cross scales, the intervention determines the applicable scale in the framework; however for many of these actions, the intervention must be designed in a way that supports action at that particular scale.

Intervention

The intervention axis describes the content of each system. Interventions are the tasks and the feedback the system provides when a user interacts with the system through the mode of embodiment.
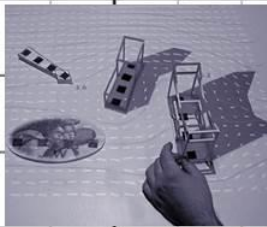
Assembly	Perspective	Effort	Size	Distance	Time	Distance	Survey/Route	Heading	Intervention
									Manipulate virtual 3D object
									Change Simulation
bo									Build and animate animal
			Ping Pong Plus						Change apparent spatial properties of table
				SMSlingshot					Show messages on walls
				Projection Mapping					Change apparent spatial properties of objects
									Appearance of environment changes based on light speed
									Feel vibrations on part of body oriented towards north

Figure 22 – The intervention axis and an example interface for each scale.

Interventions must be designed to function given the constraints of the mode of embodiment of each system. For example, an intervention that requires a user to walk around a room would not work with a system that establishes embodiment by enabling users to grasp physical objects on a surface.

Interventions also provide the link between embodiment and the aspects of spatial cognition. For example changing the design of the simulation that underlies the URP system is what relates the tangible objects to the environmental scale of buildings in a city, which ultimately engages spatial scaling ability. A different intervention could more directly engage skills related to assembly or mental rotation without changing the way the system establishes embodiment.

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Aspects of Spatial Cognition

The aspects of spatial cognition axis shows which aspects of spatial cognition a given system engages. The categories; abilities, perception, and navigation; are drawn from my analysis of spatial cognition experiments, and each specific aspect of spatial cognition is defined and shown to be linked to the body by one or more specific experiments conducted by researchers in the cognitive sciences and discussed in detail in Chapter 3.

Figure 23 – The aspects of spatial cognition axis.

The relationship between each system and the aspects of spatial cognition are illustrated by blue squares: the darker the shade of blue, the more directly the system engages that aspect of spatial cognition. While none of the systems shown on this chart have been evaluated in a way that shows a direct link to any of the aspects, my own analysis of the systems and my familiarity with the definitions of each of the aspects makes it possible to estimate how the systems lead users to apply certain spatial skills.

Trends and Opportunities

Plotting these systems together leads to several useful insights. The first is that the scale of embodiment and the type of spatial cognition that a system engages seem to be related. Figural scale embodied systems engage small scale spatial abilities; vista scale embodiment relates to perceptual effects, and environmental scale interactions are well suited to engaging aspects of cognition related to navigation. The table also highlights the fact that these are not hard and fast relationships. For example, Slower Speed of Light, one of the examples that more directly deals with linking embodiment and spatial cognition, spans across navigation and perceptual aspects of spatial cognition. Because the intervention in Slower Speed of Light actually compresses distance relative to the speed of light, it also influences perception of the relationship between distance and time. Engaging multiple aspects of spatial cognition may be a feature of systems that purposefully alter spatial features of environments and objects, although that may become more difficult as the degree of embodiment moves beyond the typical mouse and keyboard style navigation of virtual environments.

The third insight is that there are several unexplored opportunities in this design space. While the interfaces described in this document show a trend with respect to the relationship between scales of interaction with aspects of spatial cognition, it is conceivable that, for example, figural scale embodiment could engage cognition related to navigation. The upper right and lower left of Figure 20 appear to be unexplored territory for the design of embodied interactive systems. Of particular interest is the opportunity for designs that engage perspective taking ability. As the TASC case study in

the following chapter illustrates, the increasing availability of virtual reality headsets may lead to design opportunities which focus on perspective taking in particular.

It would be impossible to define all combinations of embodiment and intervention that act on spatial cognition; therefore, the design space can be considered essentially infinite, although the creation of new interfaces and the inclusion of a broader selection of previous work will fill out any gaps. Furthermore, given that spatial cognition is an element of many facets of perception and behavior, and all interaction is embodied to one degree or another, it could be possible to critique most systems using this framework. However, this framework would not be appropriate for many of those systems because they either do not establish embodiment in a way that is sufficient to influence cognition or the intervention that they include is not sufficiently related to a spatial cognition phenomena for this framework to be meaningful. Establishing embodiment and designing interventions are described in the following section, which will lead to a clearer picture of the sort of systems that are a good fit for this framework as well as how to apply this framework to the design of new systems.

Spatial Cognition Focused Interaction Design

There are two primary elements that make up an interactive system focused on spatial cognition: embodiment and intervention. Broadly, embodiment is established through the combination of inputs and outputs in a system. The intervention is the context of those inputs and outputs, i.e. the task that the user performs. Figure 24 illustrates the relationship of these two activities in the overall design process:

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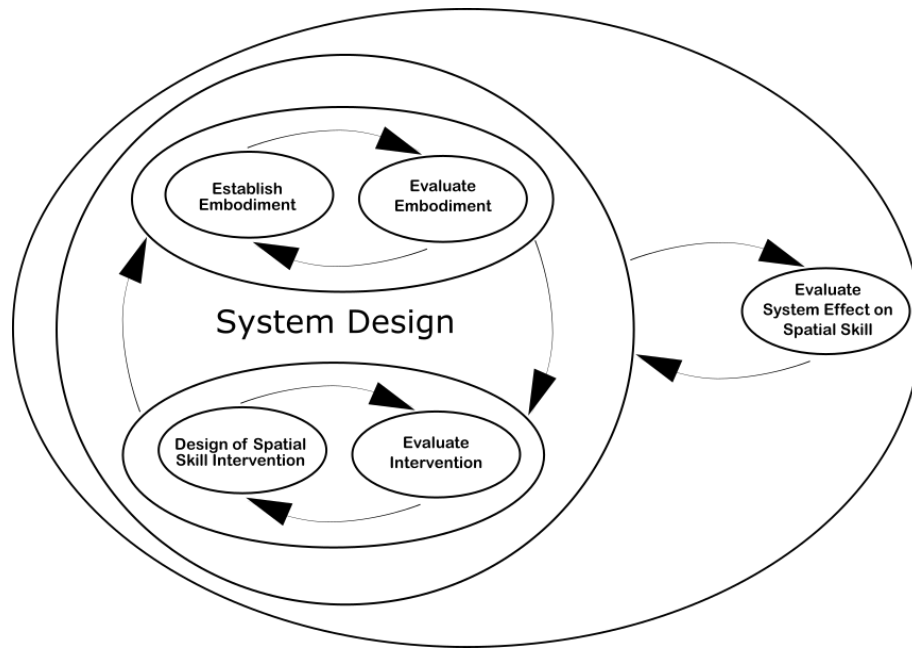
Figure 24 – Spatial Cognition Focused Interaction Design Process Diagram

Establishing embodiment and designing the intervention inform each other continuously;

however they are described here separately, because they each lead to different

opportunities and constraints that must be considered separately as well as holistically.

While this section discusses these concurrent design processes at a high level, in order to

draw out specific design guidelines, the TASC case study in Chapter 6 provides a specific

example of how a designer could enter and apply this design process.

Establishing embodiment

Establishing embodiment is the process of designing interactions, interfaces, and content

that sufficiently stimulate the sensorimotor system to engage the targeted cognitive

phenomena. Establishing a strong sense of embodiment is important given the body's

relationship among the body, action, and cognition. Without a sufficient degree of

embodiment, an interactive system will not be able to create the desired effect on

cognition or leverage cognitive phenomena to accomplish its goals. However, by

combining interaction modalities and the content of a system, designers can create systems that mimic the expectations of the sensorimotor system in ways that cause cognition to respond to digital content as if it were real. Designers can leverage this perceived reality and combine it with content in ways that lead to novel embodied experiences which can ultimately have an effect on how users perform cognitive tasks.

As I showed in Chapter 4, interactions with embodied interfaces happen on one of three scales: figural, vista, and environmental. Each of these scales also relates to several different cognitive phenomena, e.g. tool appropriation, perspective taking, or heading recall. The relationship between interaction and cognition is one-to-many (and vice versa); therefore, selecting a set of technologies and interactions as a starting point can lead to a successful system; however, it does, in some ways, limit the future selection of the aspects of cognition that the system will be likely to engage. For example, designing an interface that is based on stacking blocks (figural scale) may not be the best choice for supporting skills related to navigation (environmental scale). There are many cases where designing the interface first may be desirable: a stakeholder may request a certain set of technologies be used; space or funds may be limited, or the interface may need to accomplish other tasks that require a certain interaction scale. In these cases it is important for designers to keep in mind the interplay between interaction scale and the possible relationships to cognitive phenomena when working through the design process.

Design is typically described as an iterative process that involves ideation, construction, and evaluation. The following sections describe how embodiment can be established and how to know if a design is successful at establishing embodiment.

How do you establish embodiment?

The necessary and sufficient conditions of embodiment differ depending on the elements of cognition being engaged. Frequently, multiple senses are engaged in cognition of a particular space. Therefore, creating systems that provide the same information using multiple modalities can effectively support the establishment of a strong sense of embodiment. Tangible and embodied interfaces are particularly well suited for this because they inherently include a modality related to sensorimotor (physical) aspects of the body, e.g. touch or movement, which can be supplemented with additional modalities like sound or light.

The process of designing an interface that creates a strong sense of embodiment can start from any number of different places, e.g. technology, sense modality, or type of interaction; however, because of the link that scale makes between interaction and spatial cognition, the following process starts by selecting a scale and flows from there, but this process can easily be adapted to a different starting point depending on the specifics of any particular project. Broadly the process for designing an interactive system that establishes embodiment at a particular scale is something like this:

1. Select a scale.
    a. The choice of scale can be dictated by any number of factors including preferred technology, budget, space constraints or link to spatial cognition.
2. Brainstorm all the ways you can create interactions at that scale.
    a. Possible interactions are often determined by available technology. Different interaction technologies support different scales in different ways. For example, Microsoft Kinect™ supports free hand gestures,

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which work well for vista scale interactions. However, when Kinect is
combined with a visual representation of a body and a physical object, it
can be used to support figural scale interactions by leveraging common
coding. Objects on a tabletop support figural scale interactions very well;
however if the tabletop system is combined with a large scale projection
for which the objects are controllers, it can be used as part of a vista scale
interaction.

3. Choose one or more interaction types that can accomplish the design goals.

    a. Preferably they support each other by providing multiple simultaneous
    ways to present the same content. For example, adding tangible elements
    to a virtual reality system makes it possible to both see and feel the virtual
    objects.

4. Develop prototypes of the system to determine whether it creates the desired
effect.

    a. This process typically starts with low fidelity prototypes like paper and
    cardboard mockups, proceeds through proof-of-concept technology
    development, and leads to a system that is sufficient for evaluating how
    well the system supports embodiment. Since, for the purposes of this
    dissertation, this process is going on at the same time as the design of the
    intervention, described in the next section, it is a good idea to iteratively
    align the interaction and intervention during this stage of development.

5. Evaluate the system for its support of embodiment.

a. There are many documented phenomena that illustrate how the body relates to space. Replicating the studies that highlight these phenomena in the context of the digital interface can show that the interface does actually meet the expectations of mind and body in a way that makes it believe that what it is experiencing is real, or at least real enough. For example, common coding theory predicts that people can recognize their own body movements, even if the representations are abstract. If an interface creates a representation of body movement, evaluating whether people can recognize their own movements in that representation would show that the system both senses and displays the movement in a way sufficient to exploit common coding theory to create a cognitive effect (Mazalek et al. 2009; Mazalek et al. 2010; Mazalek et al. 2011).

6. Repeat steps three through five as needed, while simultaneously refining the intervention.

In order to create a digital interactive system that exploits the relationship between embodiment and spatial cognition, the above process often should be undertaken in conjunction with designing an intervention (content or task) that relates the interaction to the desired effect on cognition. The case studies in the following chapter illustrate the interplay between these two processes in a way that is difficult to capture through abstraction. The next section describes how to develop an intervention that acts on some element of spatial cognition.

Designing a spatial skills focused intervention

While building a system that engages the sensorimotor system in ways that support

cognition is important, linking that system to a particular spatial skill requires a carefully

designed task that exploits the link between embodiment and cognition of space.

Depending on the goals of the design, whether they are simply to engage a spatial skill

for accomplishing some task, augment spatial cognition to make up for deficiencies, or

alter spatial cognition to lead to improved spatial skills or manipulated metaphorical

structures, the task can be as simple as creating a one-to-one relationship between action,

perception, and the target phenomena, or as nuanced as an environment that alters the

spatial relationships that people rely on for accomplishing their goals. This section

describes what a spatial skill focused intervention is and why it is important, how

designers can create these interventions for their systems, and how to evaluate the

intervention.

What are spatial skills focused interventions and why do they matter?

In this context, interventions are the tasks or activities performed using an interface. I use

the term interventions because they are the aspects of the digital media system that create

the link to spatial cognition and provide the feedback necessary to support or alter it if

desired; that is, they intervene in the typical use of spatial cognition. Using the example

of *Slower Speed of Light*, the intervention could be described as move through a virtual

environment to collect items while characteristics of the environment change with respect

to changes in the speed of light (Kortemeyer, Tan, and Schirra 2013). Interventions

necessarily draw aspects of their design from the system of which they are a part. The

intervention in *URP* could be defined as moving objects to alter variables of an

underlying simulation. Grabbing and moving objects is a necessary component of interactions with the Illuminating Light system; however, it is not even an option with the mouse-and-keyboard based system that runs *Slower Speed of Light*.

Separating the design of the intervention from the interface makes it possible to take advantage of the many ways a single embodied interface can engage spatial cognition. While certain ways of establishing embodiment are suited to engaging certain aspects of spatial cognition more than others, there is never a single solution. Therefore, designing the intervention and establishing embodiment concurrently, but not necessarily as a single unit, provides both flexibility and power to the system, and can help the designer deal with complicated problems from multiple points of view. However, given that the intervention and interface rely on each other for aspects of their design, the more complicated design issue is how different interventions engage different aspects of spatial cognition and how we design for them.

The spatial skills focus of interventions is drawn directly from spatial cognition research. Chapter 3 described several experiments that linked the body to different aspects of spatial cognition. These experiments describe actions taken by both the experimenters and the participants, the conditions of the experiment, and the results of the experiment. Designing interventions that recreate or are inspired by these experiments is a good place to start when conducting research about the potential effect of digital media on spatial cognition. However, depending on the goals of the system, it may not be enough simply to recreate the conditions of an experiment that showed the link. In these cases, examining the core elements of the phenomena and designing interventions that alter the fundamental aspects related to them may be necessary.

While the examples in the previous chapters do not intend to engage spatial cognition specifically, *TOPOBO* does create an intervention that reframes certain aspects of spatial cognition through interaction. Constructing and animating a physical object links the use of the blocks to the physical concepts related to force and motion (Raffle, Parkes, and Ishii 2004). In a typical force and motion evaluation, participants view animations and are asked to predict the result of different events occurring in the animated environment. The evaluations have shown various errors made by different age ranges of participants and hint at the fact that experience with these laws leads to better comprehension of them (Harris 2014). While *TOPOBO* was not designed with this sort of framework in mind, designing an intervention that makes it possible to use *TOPOBO* to engage with the concepts of force and motion in a novel context illustrates the way that design of interventions can draw from spatial cognitive phenomena without mimicking the experiments that illustrate their existence.

The TASC and BDC case studies in the following chapter describe the design of two quite different interventions: one that recreates aspects of an experiment and another that alters a fundamental aspect of how spatial cognition is applied. The following section describes an abstraction of the process used to design a spatial skill focused intervention.

How to design spatial skills focused interventions

Designing a spatial skill focused intervention starts with selecting a spatial skill to focus on, and many of the other design decisions flow from there:

1. Select a spatial skill to focus on.

a. The selection of a spatial skill can come from a design brief stating that the interface is to support it, or it might come from the fact that the spatial skill is strongly correlated with success on some particular task that the interface should support.

2. Describe the spatial skill and how it relates to the body.

   a. Research the spatial skill both from an experimental point of view and from an applied point of view. The experimental point of view should describe the context and the tasks that experimenters use to isolate and evaluate the skill. The applied point of view will illustrate how people use the skill in the real world. Both of these aspects of the skill can be drawn on for inspiration when designing the intervention.

   b. Research how the skill relates to the body. The embodied aspect of the skill can be related to the experimental and real world aspects of the skill, but it may also relate to the body through some mediating element like metaphor or intention. The relationship between the body and skill will directly affect the choice of interface and interaction type.

3. Brainstorm high level links between interaction and the spatial skill.

   a. Assuming there are no constraints on the interface, choose the best interface for establishing embodiment that can engage the skill in question. If there are constraints on the interface, describe the ways the available interfaces can establish embodiment and attempt to link them to the spatial skill in several different ways.

4. Given the spatial skill description and the interface, describe tasks that link the experimental, applied, and embodied aspects of the skill.

    a. In this step, there may be further design constraints to consider. For example, the age and interests of users can lead to a particular type of task, or a stake holder may request a game instead of a tool. Tasks do not need to be complicated, unless complexity is required by some other goal of the system. Tasks can be as simple as touch a teapot, or move a ball with a rake.

5. Select one or more of the interventions and create low-fidelity prototypes to illustrate the main aspects of the interaction and intervention.

    a. Iterate on the prototypes to uncover pitfalls and opportunities, as well as weed out the weaker ideas.

6. Create a fully functional prototype and evaluate it.

    a. Evaluations can range from determining whether or not the prototype engages the skill to showing that the skill can be altered by use of the system. Depending on the system, evaluations can be ongoing as users interact with it over long periods of time.

7. Repeat steps four through 6 as needed.

Designing and developing these systems requires balancing many different elements that all affect the success of the system. Designing an evaluation to determine whether that balance has been struck and that the system fulfills its goals can be an equally nuanced process.

Evaluating Spatially Focused Interactive Systems

Because the interventions are so tightly coupled with the interface they rely on, evaluating the interventions separate from the interface is typically very difficult. This separation is critical because the purpose of an intervention is to improve the capabilities of the individual on the spatial skill, not just the intervention task. That is, the training should be not specific to the trained task, but *generalizable* to a wide number of tasks because it enhances the core spatial skill. However, depending on the target skill and the specifics of the intervention, it may be possible to show the effect of the interface on the intervention by conducting comparative evaluations. Once the interface has been shown to sufficiently establish embodiment, conducting evaluations that show the difference of effect between the primary system and systems that alter aspects of it may be sufficient to illustrate the success of the intervention.

Depending on the system and the intervention, possible alterations can include changing how the system establishes embodiment, the relationship between visual and physical feedback in the intervention, the complexity of the task, etc. Running comparative evaluations requires developing multiple versions of the system and intervention; however, the results of the evaluation can be very helpful in understanding and illustrating the strengths and weaknesses of the system. How to run these studies is discussed in more detail in the section Evaluating Spatially Focused Interactive Systems; however, determining which spatial skill evaluation methods to use is an important first step towards the evaluation of the entire system.

Chapter 3 describes many experiments that highlight aspects of spatial cognition and level of spatial skill. Many of those and other experimental set ups can be replicated to

study an interactive system that engages spatial cognition. Selecting an appropriate metric begins by defining the effect that the system is intended to create. For systems that influence perceptual aspects of spatial cognition, using methods for researching perception makes sense. These include self-report metrics of capability, estimations of distance, size, or slope either verbally or using representations, selection of comparable objects from an array and many others. Mental representation focused systems should be evaluated by looking at their relationship to or effect on the type of mental representation they were designed to engage. For example, an interface intended to support perspective taking should use a perspective taking test to show its effect. Similarly, interfaces meant to engage navigation skills can be evaluated using any number of metrics including straight line distance estimation, heading recall tests, map drawing, or landmark sequence recall. The case studies in the following chapter show different ways that different evaluations can be applied to interfaces designed for somewhat different effects on different spatial skills.

As noted above, selecting an appropriate evaluation is only the beginning. In order to show whether or not a system is an appropriate way to create the intended effect requires a somewhat more involved evaluation process that compares multiple systems.

Developing embodied interactive systems can be extremely time consuming and expensive. Many off-the-shelf sensing technologies are relatively unreliable; development environments and backend software often are not intended for creating complicated systems that combine multiple input and output devices, and there is even less technology available for developing systems that fundamentally alter the perceived properties of space in the ways that may be necessary for creating some of the potential

effects systems like this could create. Therefore, designers and developers often have to spend extra time just trying to get anything to work the way they intended, not to mention the time and costs associated with producing robust and repeatable systems that could be used for anything more than lab-based research. Therefore, the goal of evaluating an interactive system that engages some aspect of spatial cognition should be to show that the system achieves its goals better than anything simpler and cheaper. An evaluation method that compares an interactive system to other systems that use either modified interaction techniques, intervention designs, or both can show which elements of the system are most effective and which elements are not effective at all, as well as providing controls for some of the variables that are of interest to the designer. Since a methodology that compares multiple systems necessarily requires designing, building and evaluating multiple systems, it is worth keeping evaluation in mind from the beginning of the project. By designing flexible systems that allow for multiple controllers and multiple interventions, the labor and cost involved in altering experimental variables can be minimized.

Many spatial cognition evaluations are intended to simply asses a subject's spatial ability at one point in time. For example, a researcher will meet with dozens to hundreds of students, give them the test, and then draw some conclusions about spatial abilities in that population. Using these evaluations to show the effect of an intervention requires a different experimental protocol, which assesses changes in an individual's spatial skill over time. The protocol must minimize learning effects on the test itself and remove confounding variables that might influence the results of the test, both before and after the intervention. The data analysis must also compare results between subjects to

determine whether the effects of the intervention are specific to an individual, a subset of the population, or the entire population (Uttal et al. 2013).

Such a protocol is described by Uttal in "The Malleability of Spatial Skills: A Meta-Analysis of Training Studies" (Uttal et al. 2013). Uttal calls the preferred experimental design mixed design, as opposed to within-subjects-only design and between-subjects design. Within-subjects-only gives a spatial skills assessment before and after an intervention. Between-subjects designs have a control group that does not receive the intervention, but the spatial skill is only assessed after the intervention is given to the experimental group. Mixed design protocols give two assessments to both a control group and an experimental group. The control group takes the test twice to establish a baseline metric for the learning effect of the test as a function of performing the test twice. The experimental group is assessed before the intervention, to establish an initial measure of spatial skill, then is given the intervention, and then is assessed again. This allows researchers to determine whether improvement is due to test-retest learning effects only, or if not, to accurately establish the magnitude of the effect of the intervention (Uttal et al. 2013).

An experiment following the mixed design protocol will illustrate the effect of a single intervention on the spatial skills being evaluated, but on its own, it cannot show that the system and intervention are a better method for influencing the spatial skill than anything else. Therefore, it is necessary to run a mixed design protocol on several systems that each alter an aspect of the design that may or may not have an effect on the outcome. Evaluating multiple systems will give researchers a much clearer picture of the actual effect the system has on spatial cognition.

Conclusion

The design process described above highlights the tight coupling and the balancing act that designers must perform when leveraging embodiment and intervention to engage spatial cognition. Based on my experiences developing systems that fit in this design space, I have developed the following design guidelines related to establishing embodiment, designing interventions, and evaluating the effect of systems on spatial cognition.

Establishing Embodiment

The following guidelines relate to establishing embodiment in TEIs that engage spatial cognition:

1. Establish embodiment using techniques that **align the scale** of interaction with the target skill.
2. Focus on aspects of embodiment that can **reinforce the skill**, and avoid those that might conflict with its application or provide ways to work around the intervention.

Based on the trends seen in the design space diagram, establishing embodiment at a scale related to the target spatial skill will lead to a stronger design with few confounding variables. Because of the research showing how spatial cognition is related to the body, selecting modes of embodiment that align with the target skill will also reinforce the use of that skill in the intervention. For example, navigation in a virtual environment does not have an established link with perspective taking, so navigation cannot be supported from a spatial cognition perspective in systems that attempt to engage perspective taking skills.

Designing Interventions

The digital aspect of interventions leads to new opportunities to engage spatial skills. The following guidelines are useful for the design of interventions that attempt to relate embodiment to a target spatial skill:

1. Look for **opportunities to engage the skill** in a way that is different from how it is normally applied – exploit the digital medium.

2. **Align** intervention design with **scale** of embodiment and the target skill.

As the emBodied Digital Creativity case study will illustrate, systems do not necessarily need to ask users to perform a particular spatial task. They can instead create a situation or environment that focuses users to apply a particular skill. Looking for opportunities to create novel interactions can strengthen the design of an intervention and create new ways for users to experience the use of the target skill. Because of the tight coupling between intervention and mode of embodiment, interventions cannot create conflicting conditions. For example, an intervention that requires a user to navigate a physical space would not work well with a system that establishes embodiment at a figural scale by asking users to manipulate tangible objects.

Evaluating systems

In order for researchers to make claims about a system's impact on spatial cognition, it is important to eliminate confounding variables from the system design and to use an evaluation protocol that makes it possible to show the effect of different design decisions

on the effect of the system. The following guidelines will lead to stronger claims about the impact of the system:

1. **Mixed design studies** give evaluations before and after the intervention to show the overall effect of the intervention and to control for learning effects.

2. **Evaluate** both the **embodiment and** the **effect** of the intervention.

Mixed design studies give multiple groups of subjects a pre and post evaluation for the same target spatial skill. This makes it possible to show the impact of the system by establishing a baseline metric for the skill while controlling for learning effects. By conducting a mixed design study with groups of subjects who use different versions of the same system, for example changing the way embodiment is established between groups, researchers can show the strengths of particular design decisions as they relate to engaging spatial cognition. Because these systems are complex, evaluating the embodiment using metrics like reaction time or body part compatibility and the interventions using metrics related to user experience can lead to a more nuanced understanding of the impact different design decisions have on the results of the study.

This chapter has described, at a very high level, how to determine whether these guidelines are a good fit for a particular project and the design and evaluation processes and design decisions faced when developing a digital media system around aspects of spatial cognition. The most important point of this chapter is that each of these aspects of system design must be kept in balance during the entire design process. Every design decision affects any number of other decisions. Beginning a project with a fairly

complete understanding of its goals and the possibilities implied by the design space

defined by Chapter 3 and Chapter 4 is very helpful for maintaining this balance. The role

of domain expertise in creating nuanced designs is not unique to systems like those

discussed here, but the application of domain knowledge from the field of spatial

cognition to the design of embodied digital media systems has potential to open up new

directions for design and provide foundations that will be useful as the objects in our day

to day experience begin to be more than what they seem.

CHAPTER 6
CASE STUDIES

The case studies in this chapter illustrate the design process discussed in Chapter 5.

Comparing the two projects highlights the breadth of possibilities within this design

space and highlights the balance between the design of embodied interactions and

interventions. The evaluation of the BDC system illustrates both how to evaluate

embodiment of a system as well as how to evaluate the system's effect on a spatial skill.

The two systems described here, emBodied Digital Creativity (BDC) and Tangibles for

Augmenting Spatial Cognition (TASC), began with similar, although distinct, goals and

ended up in equally similar but distinct places. This equivalency hints at the fact that this

design process is repeatable and that it can be extended to the design of other systems

with similar goals.

emBodied Digitial Creativity

The BDC project, funded by the NSF Creative IT program (Grant #0757370), was a four

year project focused on developing tangible and embodied interfaces that leverage

common coding to improve creativity by extending body memory. In this case, body

memory is one aspect of creativity that the interface could affect. The researchers leading

this project had an additional criteria – the interface should be a physical object between

the interactor and the content of the interface, i.e. no freehand gestural interfaces. The

team shared an interest in digital puppetry and had conducted previous research about

tangible controllers for controlling virtual characters (Mazalek and Nitsche 2007).

Therefore, the project had the following goals and sub goals from the outset:

- Show that players' embodiment extends to a virtual game charters that encodes their own movements.

    o Design a tangible interface that encodes body movement in a virtual character.

    o Evaluate whether players' embodiment extends to characters when using the interface.

- Show that that extended embodiment can be leveraged to alter body memory.

    o Design and develop an intervention that leverages embodiment to alter body memory.

    o Evaluate the effect of the intervention on body memory.

I entered the BDC project as a first year master's student, and initially participated in the design of the puppet interface described below. I researched and proposed technologies, including sensors and microcontroller platforms, that would ultimately drive the interface, and I designed and tested form factors that incorporated the technology in to a single physical object. As the project progressed, I contributed to the design of the evaluations that we conducted using the interface and recruited participants and ran many of the studies, and ultimately proposed interventions that directly engaged mental rotation ability, which we used as a proxy for creativity as it relates to body movements. During the course of the project, I contributed writing to publications about our research findings and grant proposals aimed at extending our research to additional domains.

The goals of this project involved both developing an interface and an intervention; however, in order to ensure results and establish a baseline for the development of a common coding based interface, the research began by investigating ways to establish

embodiment using physical controllers and virtual characters (Mazalek et al. 2009). Research about how to establish embodiment began by using video recordings and a hand puppet and ended with a custom-built puppet controller for mapping body movement to a 3D avatar (Mazalek et al. 2010). Once it was clear that the system successfully established embodiment, we turned our attention to designing, developing and evaluating interventions that took advantage of that embodiment in a virtual environment in order to improve creativity (Mazalek et al. 2011). We then investigated the effects of the system on mental rotation and tool appropriation (Mazalek et al. 2011; Jovanov et al. 2015). This case study will describe in detail the processes the designers and researchers went through to establish embodiment, develop interventions, and evaluate the system's effects on cognition.

Establishing Embodiment

A primary component of this research was to use common coding to establish embodiment. Therefore, the research began by discussing and researching the necessary and sufficient conditions for common coding to work at various levels of abstraction. Then, we worked to develop technology and form factors that fulfilled the design goals of the interface.

Proof of Concept

Because common coding relies on primarily human-like movement, early brainstorming focused on determining the aspects of human movement that could be captured by a tangible interface and that would best trigger common coding effects. In order to determine a set of movements that would work and an appropriate level of abstraction for

those movements, our team built and tested a low fidelity prototype, Figure 25, to

replicate and build upon previous common coding research.
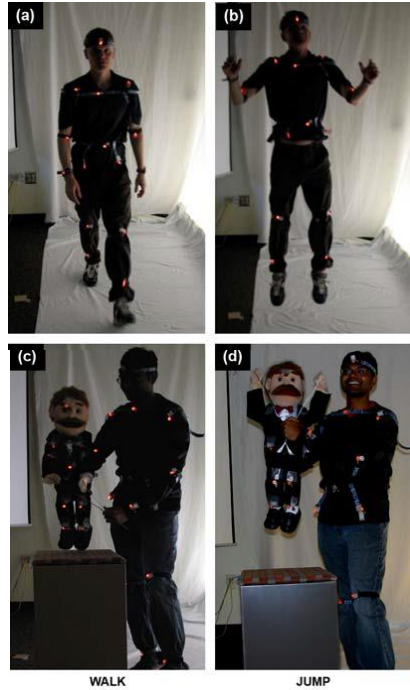
Figure 25 – Lights used to construct point-light walkers from bodies and puppets
(Mazalek et al. 2010)

Early common coding research showed that point light walkers, similar to those in Figure

26, were sufficient to trigger self-recognition (Beardsworth and Buckner 1981). In order

to determine the fidelity required to recreate the effect and whether or not people could

recognize abstract representations of the movements of an object that encoded body

movement our team built and tested a set up that created point light walkers from people

and puppets that they controlled.
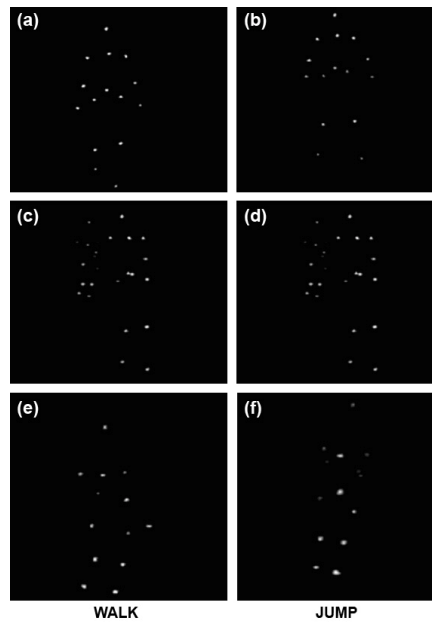
Figure 26 – Point light walkers constructed from video of participants and puppets wearing LEDs on their bodies. Items (a) and (b) show LEDs on the body only; (c) and (d) show LEDs on the body and the puppet, and (e) and (f) are created from LEDs on the puppet only.

During the study, participants wore red LEDs on 16 points on their bodies and performed sets of walking and jumping movements. Participants then held a hand puppet, shown in Figure 25 and performed the same movements. They then turned the LEDs on their bodies off and performed the movements with the puppet again.

The movements were recorded with a mini DV camera and, later, processed so that the video showed only the points of light. Copies of the videos were also processed so that the body proportions of each participant appeared to be the same.

Participants returned after a week and were shown pairs of videos, body only; body only with standardized proportions; puppet and body; and puppet only, on a computer screen. They were asked to select which of the movements were their own. Participants were able to select their own movements surprisingly well in all cases. The results of the self-recognition study are shown in Figure 27:

Mean Accuracy for Different Conditions
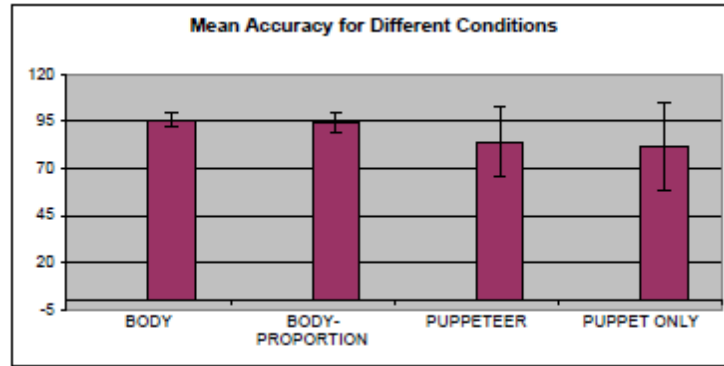
Figure 27 – Positive self-recognition scores for each condition of the experiment.

Technology

The results from this study gave our team enough information to determine that abstract representations of movements created by moving an object can trigger common coding effects. This was sufficient to move forward with designing tangible interfaces that encoded body movements for playback by a virtual character.

For the tangible interface, our team had several goals:

- Act as an intermediate device between the player and the avatar

- Work in real time.

- Cheap and portable – i.e. not require a long complicated set up and only work in certain pre-configured environments like motion capture studios.

- Capture sufficient body movement data to trigger common coding effects

These design goals were drawn from the goals of the project as well as the researchers own interests. Our team began by defining the requirements of the device and possible technical solutions to fulfilling those requirements.

Sensors

Several sensors were available for tracking movement at the time the system was developed; however few of them were robust and simple enough to meet the design goals. Initially the choice was between accelerometers, computer vision, and bend sensors at each of the joints. Each of these options had limitations that could have affected the results of the study.

Accelerometers produce very noisy data and require careful calibration, often involving additional sensors. Furthermore, the math involved in combining data from multiple accelerometers to create a representation of full-body movement would have been complicated and would have required quite a bit of processing power and time to create reliable movements.

From a technology point of view, one reason we opted for a physical interface between the player and the avatar is that computer vision requires several pieces of technology that work together in order to create useful data, which is why they often are set up in a single room and not moved. Performers in computer vision studios have to wear suits with markers that can be seen clearly by the cameras. While it would have been possible to outfit the puppet with markers, cameras used in these set ups often lose track of the markers; therefore four to eight cameras are often used at the same time, and the data from each of those cameras has to be combined in post-production to create the virtual representation of the movements. The need for post-production also means that the systems typically do not work in real time.

Bend sensors are fragile and give unstable data unless they are constrained to a relatively limited range of movement and well calibrated. They are also relatively expensive. While they could have been used to fulfill all the design goals of the interface, they might not have been robust enough to stand up to the abuse of long term use during the testing.

Because the system would eventually involve a 3D game engine, an insight about how game engines determine body position led to another sensor option – potentiometers. In game engines, body parts are oriented with respect to one another based on a rotational position of the joint that connects them. The rotational positions of each joint, when applied to the bones of the avatar in a particular order, lead to a particular body position for the character. If the interface could track joint rotation, it could track body movement, and potentiometers are basically rotation sensors. Potentiometers are relatively robust and they give very reliable data. They are cheap; they come in hundreds of form factors, and they use very little power.

Microcontroller – Arduino and multiplexing

In order to collect sensor data and transmit it to the game engine, the puppet required a microcontroller. The Arduino platform was a natural choice for this project because of its flexibility and the readily available example code for sending and receiving sensor data. The Arduino models available at the time of the project included the Lilypad and Duemilanove and the Mini. The form factor of the Lilypad fit the puppet design well, but it was designed to work with conductive thread. Connecting wires to it was difficult and led to unreliable connections. The Duemilanove was too large and uses connectors that come apart too easily. The Mini is small enough to fit in any possible form factor of the puppet and uses robust soldered connections, but it requires extra hardware to be

reprogrammed. Because of the need for solid connections and small form, the team chose the Mini after a prototype using the Lilypad proved to be too fragile for long term testing.

None of these models provided enough analog connections to read from all 16 sensors the puppet would use. Multiplexers are digital circuit components that use digital pins to switch which sensor is being read and sent to the microcontroller. One version of a multiplexer uses four digital pins and one analog pin from the microcontroller to read and transmit from up to 16 different analog sensors. This made it possible to use a single microcontroller for the entire puppet.

Connectivity – Bluetooth

Because of the wide range of movements that people would perform using the puppet, the puppet needed to be wireless. Because of its relatively wide availability, Bluetooth was the natural choice for achieving that goal. While the use of Bluetooth did not constrain the design in any particularly drastic way, it did lead to development problems, short battery life, and some instability in the system.

Pairing Bluetooth devices using Arduino is a difficult process because it requires a complicated initial setup process that is difficult to repeat across multiple Bluetooth radios. The setup process requires the use of a serial terminal to send the pairing instructions from the computer through the Arduino to the Bluetooth module. This process often fails without giving any feedback about why. We were only able to successfully pair one Bluetooth module with the computer running the game engine software. This meant that at any given time only one puppet could be used.

Bluetooth radios require a lot of power as far as small electronics go. The puppet used a nine volt battery for power, which only lasted for four to five hours when powering the radio. This meant that, to ensure proper functioning, we had to replace the battery before each user study session. While replacing the battery was easy, the batteries were expensive, and when they began to run out of power, the system behaved erratically.

When the Bluetooth radio or the computer failed to receive or transmit some piece of data or if the data was corrupted, the system failed in one of any number of different ways. Sometimes it would completely freeze, requiring a complete reboot. Sometimes, it would arbitrarily position one or more limbs, causing the avatar to appear uncalibrated. Sometimes it would just flicker in an odd way and continue working normally. These errors could be caused by a low battery, a faulty radio signal, distance between the transmitters and receivers or just a loose wire somewhere in the puppet. Typically restarting the puppet would fix the problem; however connections between the sensors, the microcontroller, and the Bluetooth module frequently needed to be repaired in order to ensure seamless communication.

Game Engine

During the time that BDC was being developed, few game engines were readily available for academic research. The UnReal engine was expensive for a full license, and the limited versions that were available for personal and educational use had limited functionality and development for UnReal was extremely specialized. Unity had barely been released. However, an open-source option, Movie Sandbox was gradually becoming an option, and by working with the developer of the engine, we were able to get the features required for our research prioritized.

Working with an engine that was still in development did cause some development

delays, and led to some tradeoffs with fidelity of the rendering and efficiency of the

processing. However, having direct access to joint rotation data structures and the

software for communicating with different controllers made it possible to develop the

puppet and the intervention along with the engine. The limitations of the engine became

less and less of a factor as its development progressed along with the BDC project.

Form Factor

While the sensing technology was being discussed, the form factor was also being

worked through. Because of the strong link between an interface that encodes body

movement and traditional puppetry, we began by investigating different types of puppets

and the pros and cons of each. Figure 28 shows the relationships between expressiveness

and ease of use for several different puppet types:
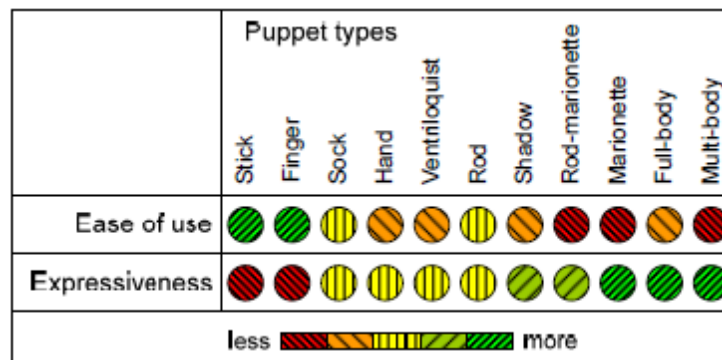
Figure 28 – Different types of puppets rated for ease of use and expressive potential
(Mazalek et al. 2011)

The interface needed to encode movement from the whole body, but it also needed to be

portable and easy to use. Striking a balance between these led to the design of a hybrid

full-body/rod puppet shown in Figure 29. This design hangs between the player's

shoulders and knees. The limbs of the puppet act as scaled down versions of the player's

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limbs. The player has direct control of the puppet's arms, and the movements of the puppet's legs mimic those of the player due to the placement of the joints.

Figure 29 – The BDC puppet, a hybrid full-body/rod puppet that balances ease of use and expressivity to track full body movement of the puppeteer.

The system only takes a few minutes to set up and learn. While it is not as easy to use as a plain stick or rod puppet, it is probably easier to control than a hand-and-rod puppet like a Muppet. In the case of expressivity, because of its close connection to the player's body, it is not as broadly expressive as something like a Muppet or a typical full body puppet that takes on an identity of its own, but that same connection is leveraged to include 16 degrees of freedom, which leads to an increase in possible expressivity for the avatar that ultimately depicts the movements.

Combing Technology and Form Factor

The choice of sensors and the design of the puppet's form led to several problems. Mainly, joints that rotated in multiple directions could not be sensed using a single potentiometer, and control of the puppet's head was not easy to accomplish.

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Shoulders and hips can rotate in multiple directions, and capturing that rotation is important for creating believable body positions for the virtual character, and if the puppet's legs did not rotate properly, the player's movements would be restricted causing the player to move in an unnatural way.

There were several attempts to create somewhat complicated solutions to this problem. Ball and socket joints are typical in puppetry for shoulders and hips, but they are not well-suited to being combined with sensors; they have too much freedom to move in arbitrary directions. This led to an attempt at designing a custom ball and socket joint with embedded resistive sensors, but before that design made it into prototyping, a simpler solution became obvious.

Mounting two potentiometers with axes 90 degrees from one another made it possible to move the arm or leg into essentially any position. Figure 30 shows the configuration of the potentiometers in the shoulder joint. This design further mirrored how the game engine would handle rotational position of the joints. The joint first rotated around the x-axis and then around the y-axis, which yielded the correct position of the bone.

Figure 30 – The shoulder join of the puppet with potentiometers mounted perpendicularly to allow a full range of motion in the x, y, and z planes.

Fitting the technology and form factor together was an engineering exercise involving adding supports for the potentiometers at the joints, and creating structures for the bones that incorporated the sensors, moved in the correct directions, and created the appropriate form for the puppet.
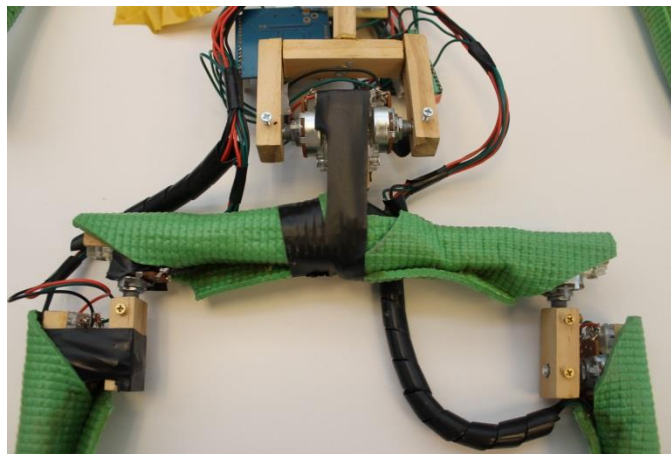
Figure 31 – Several examples of the puppet's bone structures and plastic mounts that incorporate the sensors in to the hip and waist joints.

With the bones and joints in place, attaching the microcontroller, battery and running the wires was relatively straightforward; however several minor problems became apparent,

which were solved during construction. Wire gauge, for example, trades strength for flexibility. Striking a balance between the two is important for this project because the wires are put under some stress during movement. Thick solid core wire prevented the puppet from moving naturally, while very small stranded wire broke too easily. Determining the best size was essentially done through trial and error.

This interface was not designed with ease of assembly in mind, and, in fact, several of the design problems were first encountered during assembly. For example, the mounts used to hold the potentiometers to the structural "bones" were first conceived and later refined during the assembly process, when it became clear that epoxy on its own would not hold the sensors in place. The design also did not consider durability. The potentiometers were used as a primary structural component and regularly broke because they were exposed to forces that they were not designed for.

Only three of these puppets were ever built. Each version was slightly refined and solved some of the problems; however, without another focused round of engineering, these puppets would not be appropriate for use outside of a laboratory setting. Designing for assembly, to make the process faster and more consistent, and for durability, to make it possible to use the interface unsupervised, would be important for conducting research using an interface like this in longer term self-directed studies required to show effects on STEM success or other broader impacts.

Designing Interventions

The puppet interface was used in two main rounds of evaluations, and therefore, two main interventions were designed. The first intervention was to show that the system

established embodiment in the expected way and the second was to show the effect on creativity.

Embodiment Intervention

The intervention designed to show that the system established embodiment as expected was fairly simple once the system worked. In fact, the intervention was simply to perform a set of movements while wearing the puppet. Designing this intervention involved selecting a set of movements that could be performed easily using the puppet and setting up the game engine to be able to record and play back those movements.

The design of this intervention was essentially dictated by the experimental design of the evaluation it was to be used for. The experiments aimed to test self-recognition of movements when performed by an abstract avatar. We needed several movements and wanted to know if there was a difference in recognition between walking movements and non-walking movements. Therefore, we determined that the intervention would include the following six movements: normal walking, walking with arms stretched out to the side, walking with arms on hips, tossing a ball from one hand to the other, doing the twist, and drinking from a cup.

In order to replicate the self-recognition tests that used point light walkers, it was important that participants not see the avatar while they were performing the movements. Therefore, the game engine was set up to record the movement data and play it back later.

The intervention, then, consisted of the following three steps:

1. Experimenter helps participant put on puppet and asks them to practice using it for a few minutes.

2. Experimenter demonstrates the movements and asks the participant to perform each of the movements several times while wearing the puppet.

3. Experimenter records the data in the game engine while the participant performs the movements.

This intervention illustrates how simple these designs can be. While this intervention could not stand on its own, it is important to note that evaluating whether a system sufficiently establishes embodiment before using it in more sophisticated ways does not have to be particularly complicated and can be very valuable for refining the system if needed.

Creativity Intervention

The design of the intervention for supporting creativity was somewhat more complex. First, we needed to come to an agreement about what was meant by creativity and how it was related to body memory. Next we had to work with what was technically feasible using the system. Only at that point could we design and develop an intervention that attempted to engage cognition in the intended way.

Defining creativity and body memory

The goal of the grant was to support creativity by affecting body memory. Therefore, creativity had been implicitly defined as access to and ability to perform movements as part of a creative practice, e.g. dance. The intended method for augmenting body memory was to induce a strong identification between the player and avatar, then gradually alter

the movements of the avatar, which would, over time, cause the player's own movements to become more like those of the avatar. This approach presented several major challenges:

- There are no preexisting definitions of the key characteristics of movements. Therefore, there are no metrics for measuring similarities of movements and no software for altering those characteristics.
  - o Developing any one of those elements (definitions, metrics, movement-focused software) is a long term research project on its own, each of which would require a year or more of data collection from both people who move professionally and laypeople.
- Body memory is poorly defined, and its link to creativity, apart from its importance to performing arts, is unclear.
- Real-time manipulation of body movements would require sophisticated predictive algorithms and extremely powerful computers, essentially performing post-processing, as used in motion capture systems, automatically and immediately.

These challenges made it impossible to conduct the body-memory study as it had been initially conceived. Therefore, we focused on a different type of creativity – problem solving. Problem solving is at least as broad of a concept as body memory; however, it can be split in to several more focused domains. In this case, we focused on the link between mental rotation and problem solving in STEM fields. Shifting focus towards problem solving opened up the possibilities for the design of the intervention and provided preexisting metrics for evaluation.

The design of the mental rotation intervention began by investigating the link between the body and mental rotation, which is discussed in Chapter 3. The understanding that the ability to mentally rotate objects is linked with the real world experience of objects rotating led us to consider an intervention that leveraged the self-recognition type of embodiment to force participants to engage with a world that rotated differently than expected.

Because the system had been designed with a focus on body movement, building large, complex environments with many objects would not have produced the desired results. At best, that solution would have replicated the real world experience of rotating objects. However, considering the problem from a common coding point of view led to the design of a novel intervention that involved rotating from a different reference frame. Making objects rotate in strange ways may be difficult, but making the frame of reference rotate around the objects just requires moving the in-game camera around in the virtual environment, and because common coding had been shown to support identification across frames of reference, this experience of rotation engaged the motor system of the player.

Once the rotation method had been determined, we designed a task for players to perform in the rotating environment. The task needed to cause the player to engage with the relationship between the virtual body and the virtual environment. Because movement through the environment was not supported by the system, it needed to require the virtual body to interact with objects in the environment. To support this, we came up with a simple task – use a controller to reach out and touch teapots that appear in various positions around the virtual body while the camera is moving.

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The camera moves continuously so that the player has to consistently mentally rotate the frame of reference he is working within to reach the correct position of the teapot. For example, as the camera moves from in front of the avatar to behind it, a teapot that was on the left of the screen moves to the right of the screen, although its position relative to the avatar stays the same. This requires the player to learn to reach from the avatar's point of view instead of from his own. It is possible that this embodiment of the avatar in a rotating environment is what led to the observed effect on mental rotation.

Evaluating the system

With the task designed and developed, establishing its effect on mental rotation, and the relative effectiveness of the system in general, required the design and execution of a thorough evaluation. The evaluation focused on two main questions:

1. Does an interactive system that creates an embodied experience of a novel rotational environment alter mental rotation ability?
2. Does an interactive system that establishes embodiment through tangible interaction and common coding better influence mental rotation than systems that use more traditional controllers.

Aside from a way to quantify mental rotation ability, answering these questions required a study that showed a change in mental rotation ability after using the system and a way to compare that change to other systems. To show a change in mental rotation ability, the study needed to establish a baseline mental rotation ability score for each participant. This meant that participants took a mental rotation test before using the system as well as after. To investigate how the puppet controlled system compared to other controllers, we

conducted the same study using the puppet controller, a mouse and keyboard controller

and an Xbox™ Controller.

The mental rotation evaluation, shown in Figure 32, asked a participant to view an

animation of a shape rotating on a computer screen. It then showed a different shape and

asked the participant to select, from a set of four images, the image that showed the shape

if it had been rotated like the animation.
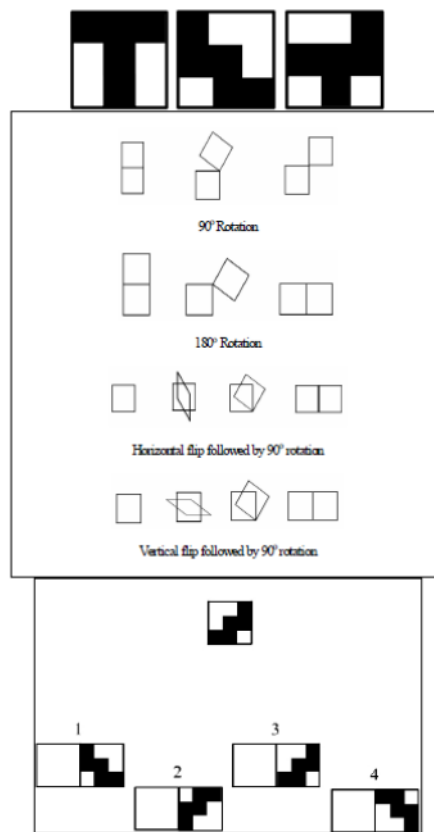
Figure 32 – An example of the mental rotation evaluation used in the BDC study
(Mazalek et al. 2011)

Researchers tracked the number of correct answers and how quickly participants

answered the prompts. Analysis of the data showed that the embodied puppet interface

lead to the largest improvement in score and greatest reduction in time to answer, which

indicated that the puppet interface and rotating teapot intervention not only had an effect

on mental rotation, but that the puppet interface also improved mental rotation more

effectively than a keyboard or standard video game controller. The results of the study

are shown in Figure 33:
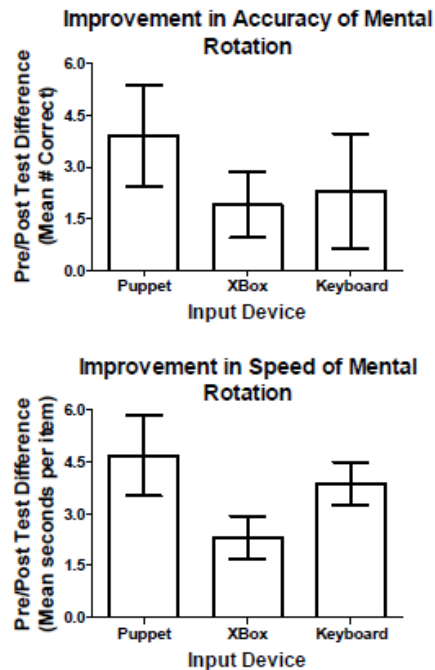
Figure 33 – The results of the BDC evaluation showing that the puppet controller led to
greater improvement in mental rotation scores and decreased the time needed to answer
mental rotation questions (Mazalek et al. 2011).

The evaluation did not directly control for learning effects by having a group take the test

twice without engaging with an intervention; however, because learning effects related to

taking the test twice can be assumed to be consistent across the people who used each

intervention, the relative improvement in mental rotation score for the interfaces holds.

With respect to the research questions, then, each interface acts as a control to the other.

With this in mind, this evaluation followed the mixed-design protocol described in

Chapter 5 very closely. While we did not have Uttal's definition in mind when designing

this experiment, this case study illustrates the power of that protocol to both assess an

intervention's effect on spatial ability while controlling for effects of learning and of the interface itself (Uttal et al. 2013).

Tangibles for Augmenting Spatial Cognition

The TASC project began in 2013 with the intention of further investigating the ways that embodied interaction and digital media could improve spatial skills, with a particular focus on how that effect could be leveraged to support STEM education. The research is funded by the Canadian Social Sciences and Humanities Research Council (SSHRC) and is ongoing. The framework presented in this dissertation is part of the early stages of the research being conducted as part of the grant. The project described in this case study is a first attempt at designing an interface from the ground up based on the research discussed in this dissertation, and as a proof of concept test of the design framework.

I have played an important role in the conception and execution of the TASC project from its earliest moments. After wrapping up the mental rotation experiments using the puppet from the BDC project, the team began investigating other possible uses for the puppet, which included rehabilitating stroke victims and supporting other types of spatial skills. In order to support this research, I began investigating the link between the body and other aspects of spatial cognition. My early research about supporting intuition in four-dimensional spaces did not lead to a specific research project; however it did make us aware of the breadth of spatial skills, the evaluations that are available to support them, and their link to success in STEM fields. Based on my research, the team realized that it would be valuable to apply our research approach to the design and evaluation of embodied interactions intended to support spatial skills for STEM learning. We submitted a grant proposal to SSHRC, of which I wrote sections focused on the relationships

between spatial skills and STEM education, design and evaluation methodologies, and contributed to the definition of our research goals and approaches.

Once we were awarded the grant from SSHRC, I continued my research about spatial cognition and embodiment, while leading a team of undergraduate students in the design and prototyping of the system that this section describes. Under my guidance, the students designed and prototyped an interface that combines several technologies to engage the body with an intervention intended to engage perspective taking skills. The students produced wireframes and storyboards to illustrate their designs and produced several iterations based on my feedback and research related to spatial cognition evaluations. Currently, I am consulting with a team on refining the intervention and designing a study that will show the effect of the system on perspective taking abilities.

This project started in the spring of 2014 and involved a team of undergraduate students at Ryerson University enrolled in a research and design course. I led the group by directing their research efforts, teaching them design skills, and facilitating their design and development work. The group was challenged to design and develop an embodied interactive system that supported a spatial ability. The design process was derived from an earlier version of the framework presented in this dissertation that more heavily relied on spatial ability metrics. The students completed the design and early prototyping of the project during the initial semester. Development of the interface continued over the summer and fall, and evaluation will take place during the spring and summer of 2016.

The interface, in its current state, aims to support perspective taking ability by establishing embodiment in a virtual reality environment. This case study discusses how

the system establishes embodiment, the design of an intervention for supporting

perspective taking and one possible approach for evaluating the system.

TASC Stakeholders and Design Process Flow

While the following sections will describe the TASC design process in detail, including

discussions of technology development and iterations of the intervention design, the

project can be used to illustrate how the design process and guidelines described in

Chapter 5 can be entered and applied by designers who hope to engage spatial cognition

with an embodied interactive system. In the case of TASC, the initial conditions of the

project were established by a design brief based on the goals of the project and the

individual interests of the stakeholders working on the project.

Design Brief

The design brief for this part of the TASC project is drawn from the goals of the funded

research and can be broadly stated as "design and prototype a tangible and embodied

interface that engages spatial cognition". Because the grant focuses on supporting spatial

cognition for STEM learning, the aspects of spatial cognition the design focused on were

restricted to small scale spatial abilities, since those have been directly linked to interest

and success in STEM subjects. Since BDC had already established a design for

supporting mental rotation, we started our design process with a focus on scaling,

perspective taking, or navigation and quickly moved away from navigation for reasons

discussed below.

Stakeholders

The stakeholders in the TASC project included the students working on the project, me and my research agenda, and the primary investigator (PI); Ali Mazalek; each of whom brought a different focus and constraint to the project. The students were particularly interested in developing an application for the Oculus Rift VR headset. This gave the team a starting point for establishing embodiment: head tracking and visual perception of a virtual environment. My interests focused on refining the design process and teaching the students design skills, and the PI's focus included teaching the students to conduct research and furthering the research related to the grant.

The following graphic highlights the initial conditions for the design process and the elements that were added as the iterative process of design progressed:
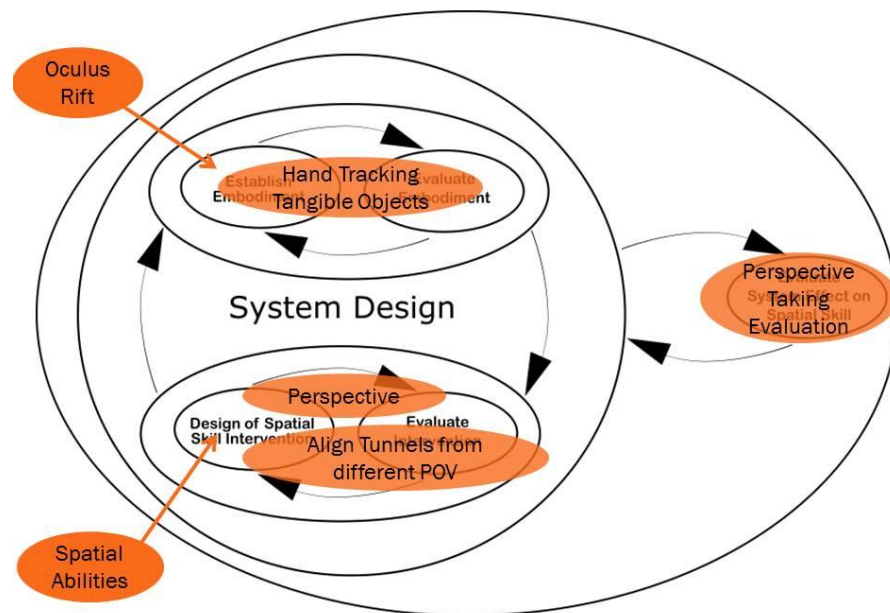
Figure 34 – The TASC design process illustrated on the high level design process discussed in Chapter 5.

The initial conditions, Oculus Rift and small scale spatial abilities provide entry points for establishing embodiment and designing the interventions. The iterative process that led to the additions of hand tracking and tangible objects to the methods of establishing embodiment and to the focus on perspective taking through an alignment puzzle are described in the following sections. The system is currently being refined and will be part of an evaluation focused on perspective taking abilities over the next several months.

Establishing Embodiment

Based on the success of the BDC project, design goals for the TASC system included leveraging common coding and tangible objects to establish embodiment. The personal goals of the design team led to the additional goal of using a virtual reality headset as part of the interface. Ultimately, these criteria led to the design of a system that establishes embodiment in three main ways: virtual reality headset with included head tracking, tracking and displaying hand movements in the virtual environment, and physical-virtual analogous objects that make it possible to see virtual hands grasping virtual objects and feel your physical hands grasp the same object in the same location.

Virtual Reality and Head Tracking

Undergraduate courses that focus on applied research and design often take unexpected directions. In many cases this is because students are frequently encouraged to pursue their own interests in ways that show their comprehension of the material and take advantage of their particular skills. Running this project as part of a course meant that it was necessarily shaped by the students in the TASC group. In this case, these students brought a particular interest in designing and developing a system that used the Oculus

Rift virtual reality headset. The incorporation of virtual reality became one of the early

decisions about the interface, which ultimately influenced many of the other design

decisions the team made during the rest of the process.

To some degree, the Oculus Rift establishes embodiment on its own. It creates a very

good illusion of depth by displaying a slightly different image of 3D modeled

environments to each of a wearer's eyes. It also tracks head movements of the person

wearing it, which makes it possible to look around a virtual environment as if it were real.

Finally, by completely blocking peripheral vision, visual distractions from the real

environment do not break the wearer's immersion. While these factors create a strong

sense of immersion in certain types of environments, it is still not clear whether the

Oculus Rift, on its own, is enough to create a strong sense of embodiment in a virtual

space.

Hand Tracking

Oculus Rift, by default, does not provide a visual representation of the player's body, and

typically, common coding is triggered when observing movements (although it should be

noted that the consistent pairing of head movements with a related and meaningful

change in visual information may provide sufficient "embodiment" or situatedness in the

environment, note that not providing a visual representation of the body leads to a

"disembodied" situatedness in the environment). The design of the TASC system, as with

the BDC project, aimed to leverage common coding to create a strong identification with

the virtual body by tracking and visualizing the body movements. In a virtual reality

environment, the source of the body movement could be the player's own movements or

movements of an avatar generated by some other source. The movements could also be

viewed from a first person or third person perspective. Given the time, resource and space constraints of the project and the availability of readily available software and hardware that tracked a player's hands and displayed their movements as virtual hands in the virtual environment, our team decided to include hand tracking in the system as a way to visually represent the player's body movement. Tracking a player's entire body would require a multi-sensor set up in a large, empty space, and asking players to walk around with essentially a heavy blindfold on could be dangerous. However, not tracking the player's whole body makes it difficult to include movement through space in the intervention without using a secondary controller, which could break any illusion created by included physical-virtual analogs in the system.

By researching different ways to add body movement to the virtual environment, our team found an off the shelf software/hardware solution that tracks hands using a LEAP Motion and displays them in a virtual environment using the Unity game engine. Games built using Unity can also easily incorporate Oculus Rift, so combining Leap Motion and Oculus Rift was relatively straight forward, at least for a rough prototype. The Leap Motion sensor is attached to the front of the Oculus Rift headset so that it detects the player's hands from the appropriate point of view. The main issue with this set up is that the sensor relies on limited information (distance data) to reconstruct a complicated structure (the human hand), so it often misinterprets the hand position and shape. This leads to a broken representation in the virtual environment. It also does not handle occlusion very well, so grasping a real world object causes the hand to disappear from the environment. These issues have mostly been solved in software as the system has continued to be developed. Figure 35 shows a player using the TASC system:

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Figure 35 – A player wears an Oculus Rift headset with a LEAP motion sensor mounted to the front.

Since the Oculus Rift only provides visual feedback, simply representing a user's own body movements in the virtual reality environment may not be sufficient to create a strong sense of identification between the user and the avatar. Seeing body movements is enough for people to know that they are in control; however, the fact that their physical movements relate to an entirely different environment than the virtual movements may break that illusion. While movements viewed from a first person perspective may not typically be included in discussions of common coding, if they are sufficiently disassociated from the proprioceptive experience of the body, the link between observation and the motor system may hold. A visual representation of movement provides one way to create identification, but it may not be enough.

Physical Blocks

In order to reinforce the connection between the player's body and the body and objects in the virtual environment, the team decided to create physical objects that were representative of virtual objects. When a player reached out to grab a virtual object, he would feel a physical object with the same shape in the expected place. Adding a physical connection between the real and virtual environments can add to the sense of embodiment in the virtual space by adding tactile and proprioceptive information to the experience, but how to match up the physical objects with the visual elements of the virtual environment leads to both a technical challenge, and a design question related to the design of the intervention.

The design question essentially boils down to what shape and size the blocks are and where they are in relation to the player. These decisions are answered directly by the design of the intervention described below. The short answer is that the blocks have the same size, shape, and location as they appear to have in the game. The technical question partially hinges on the answer to the question of size and shape, but its solution space is somewhat smaller. The solution could be as simple as designing an intervention that includes objects that can be touched, but that do not need to be tracked, by, for example, attaching them to a wall in front of the player. If the intervention does need to keep track of the objects, there are only a few existing technical solutions for tracking objects, many of which involve computer vision, e.g. MS Kinect; OpenCV; and ReactiVision or CCV. Another possibility is to fit the objects themselves with sensors that track orientation and movement, e.g. IMUs or tracks that move potentiometers. Our team investigated several of these options and eventually chose to use objects on the surface of a DSI based

interactive tabletop. The advantages of this choice include the fact that the tabletop's

object tracking is robust and the data it outputs is relatively easy to use in a Unity based

game. The main disadvantage is that it places several constraints on the positions that the

player and the objects can have relative to one another. Basically, the objects that the

player can grasp must be displayed from a point of view that is analogous to standing

next to and looking down at objects on a table top. However, in this proof-of-concept

case, a robust tracking system is more important than flexibility, and, as the intervention

will show, there are lots of ways to hide the tabletop in virtual reality.

Designing Interventions

The intervention described here focuses on perspective taking skills. The choice to focus

on perspective taking was made by our team during the research and design phase and

was driven by availability of an evaluation method and the link between perspective

taking and embodiment. The intervention itself balances these aspects of perspective

taking with the physical and technical aspects of the system in a way that forces a player

to solve a puzzle using information from two different perspectives. Figure 36 shows

various aspects of the intervention:
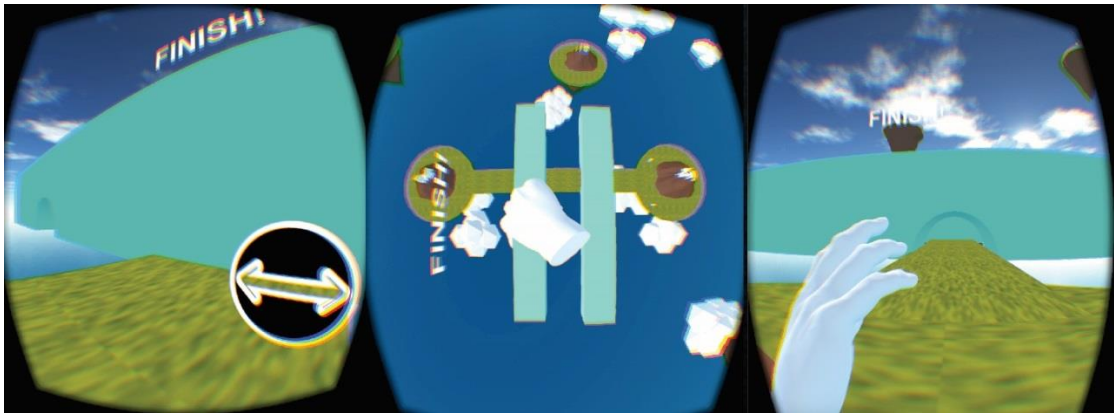
Figure 36 – The image on the left shows the environment from the first person perspective. The tunnel is visible in the left and the icon switches perspective. The middle image shows the payer's hand grasping one of the blocks from the bird's eye view, and the image on the right shows the tunnel lined up with the bridge.

During the intervention, a player wearing a VR headset stands on a virtual platform. In front of her is a bridge that is blocked by a large rectangle. Looking to her left and right, she can see that there is a tunnel through part of the rectangle that is not lined up with the bridge. She can see her hands in front of her, and when she holds them up, she begins to move forward along the bridge. Near the rectangle blocking the bridge is an icon. When she touches the icon, she switches to an overhead view which shows the platform, the bridge, two rectangles blocking the bridge, and her hands. She is high above the level and her virtual hands are large enough to grasp and move the blocks. She reaches out for one of the blocks and feels one of the physical blocks, which she grabs and slides forward and backward. The virtual block moves along with the physical block. When she has positioned the block so that the tunnel lines up with the bridge, she touches another icon to switch back to the perspective of standing on the bridge and holds her hands up to walk across the bridge. This intervention requires using knowledge gained in one perspective to the solution of a puzzle from a different perspective.

The team began the intervention design by researching spatial skills with existing evaluations and looking for links between the skill and the body. Early options included mental transformations, decomposition and assembly, navigation, sense of direction, spatial orientation, object location memory, as well as perspective taking. Of these options, perspective taking had the clearest link to the body, especially when discussed with respect to common coding and had a very well defined evaluation. Many spatial skills, like navigation, directly involve the use of the body; however, the way the body and skill relate on a basic level is unclear. Designing an intervention that applies those skills would be straightforward, but it might not fundamentally alter the way those skills are performed. Systems to support those interventions would also pose new technical challenges. For example, an intervention built around navigation that also engaged the body would, in many cases, need to track the entire body as it moved through an environment. Perspective taking, however, is a skill that inherently involves viewing the environment from the point-of-view of another body, which makes it an ideal candidate for a virtual reality based intervention.

Other skills do not have a single, well-defined, evaluation method. Some skills, like sense of direction, rely on self-report metrics, while others are measured using reaction times that primarily highlight some phenomenon. Perspective taking, like mental rotation, has a test that can be given to a participant before and after the intervention to show a quantified change in the use of the skill. Designing a system that supports a similar sort of skill could reinforce the findings from the BDC project, leverage existing evaluation methods (mixed-design) and metrics, and provided a useful first test case for the design guidelines and the technical features of the system. Perspective taking is not the only skill

that could work in this case, but during brainstorming and design sessions, it is the one that led to the most interesting design for a VR game.

While the focus on perspective taking has several advantages, its selection was ultimately driven by the interventions that it inspired. Each member of our team proposed several interventions based on any of the skills mentioned above. For example, one intervention intended to engage spatial scaling ability by creating a puzzle that required the player to increase or decrease the size of his body to be able to find solutions to a maze. Another was a construction focused intervention which leveraged scale to create more and more refined architectural elements. Many of these interventions did not include a tangible component, or involved some technical hurdle that could not have been overcome in the remaining weeks of the course. The perspective taking intervention constrains the scale and perspective at which the player can manipulate the world; therefore, the physical objects can be constrained in the same ways. It also incorporates embodiment in a more discreet way, there are two bodies involved instead of a single body with continuously varying properties, which may better engage spatial cognition by giving the player more defined reference perspectives from which to work.

The design process is rarely direct. The final result is often a mash up of the best elements of several ideas. The generation and critique of possible designs leads to a better understanding of the variables that the design must balance and which design decisions best optimize those variables. The TASC intervention is no different. The system and the intervention informed each other continuously, as did the context that the design process occurred within.

Evaluating the system

The TASC system and the perspective taking intervention have not yet been evaluated with respect to the goals of this framework; however they have been part of a workshop to determine the possibility of using similar tools in STEM classrooms. The results of that study are forthcoming. Future evaluations of the TASC system could include studying its effect on perspective taking ability and investigating the role of the different ways it establishes embodiment.

Using a mixed design approach will make it possible to determine the system's effect on perspective taking ability. The study will require two groups. First, each group will take the perspective taking evaluation described in Chapter 3. Next, one group will use the TASC system to solve the perspective taking puzzle, and the other group will do nothing. Finally, both groups will take the perspective taking test a second time. The results from group that does not use the TASC system will establish a baseline learning effect associated with taking the test twice. Any improvement of the scores from the group who does use the TASC system over and above that baseline can be linked to the use of the system.

Evaluating the different ways the system establishes embodiment can be done by conducting a separate study, or by adding more groups to the perspective taking study. In this study, each group would still take the perspective taking test twice, but the TASC system would be slightly altered for each group. One group would use the TASC system as described in this section. The other groups would use the system with various embodied aspects removed. For example one group could use the system without the tangible blocks, and one group could use the system without the Oculus Rift™.

Differences in the perspective taking scores of each of the groups could indicate which aspects of embodiment are the most important to the system.

The main drawback to this method is that it does not actually establish which aspects of the system create a strong sense of embodiment, only which ones have an effect on perspective taking ability. An evaluation of the degree to which the design elements of the system establish embodiment would require the use of a study similar to the self-identification study described as part of the BDC project. However, in the case of TASC, a different metric would likely be necessary because the system does not display full body movement and engages the body in several different ways.

Furthermore, it is possible that the TASC system will not show an effect on perspective taking ability. In BDC the effect on mental rotation was observed after ten minutes of performing a continuous mental rotation like task in the game. The perspective taking intervention in the TASC system currently only includes one puzzle, which depending on the player could take only one or two minutes to solve. It may be necessary to design more puzzles or a different intervention entirely in order to observe and effect from using the TASC system.

Conclusion

The case studies presented in this chapter illustrate the application of the design process described in Chapter 5. The results of each project are interactive systems that leverage embodiment to engage some aspect of spatial cognition. Starting from distinct objectives, each project followed a similar process to create unique solutions, each of which falls within the design space defined by the framework in Chapter 5. The BDC and TASC

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projects establish embodiment in different ways and engage spatial cognition through different interventions, but illustrate that the process described in this dissertation is a valid way to design interactive systems for this design space. The following figure places BDC and TASC in the design space:

Aspects of Spatial Cognition

Embodiment		Abilities					Perception				Navigation			Intervention
		Mental Rotation	Scaling	Force & Motion	Assembly	Perspective	Effort	Size	Distance	Time	Distance	Survey/Route	Heading	
Figural	Point and click	FoldIT												Manipulate virtual 3D object
	Move physical objects on table		URP											Change Simulation
	Combine blocks and move them			Topobo										Build and animate animal
Figural/Vista	Move puppet; view own movements	BDC												Touch teapots near body while camera moves to change perspective
	Switch perspective; move blocks; navigate VE					TASC								Use info from first person to solve a puzzle from third person
Vista	Hit ball						Ping Pong Plus							Change apparent spatial properties of table
	Aim and shoot slingshot								SMSlingshot					Show messages on walls
	N/A							Projection Mapping						Change apparent spatial properties of objects
Environmental	Arrow keys								Slower Speed of Light					Appearance of environment changes based on light speed
	Walk around												feelSpace	Feel vibrations on part of body oriented towards north

Figure 37 – BDC and TASC combine aspects of figural and vista scale embodiment to create systems that expand the design space define in Chapter 5.

With the description of the design process of BDC and TASC in mind, placing them in this table highlights the ways that the interests and skills of the design team as well as the focus of the project can lead to different ways to establish embodiment and different types of interventions. Specifically, BDC and TASC expand the design space by combining figural and vista methods for establishing embodiment and engaging perspective taking skills.

Establishing Embodiment

Because of the interests of the design teams and the research goals for each of the

projects, the BDC and TASC systems establish embodiment in different ways; however

each system leverages that embodiment to engage an aspect of spatial cognition. BDC

leverages common coding effects to establish embodiment from a third person

perspective. TASC uses head and hand tracking to establish a first person sense of

embodiment from different perspectives and at different scales in a virtual space. Both

systems include a tangible component but for different reasons. TASC relies on the

tangible component to create a link between the virtual environment and the sensorimotor

system through the sense of touch. The tangible puppet controller of the BDC system, on

the other hand, serves as a full body motion sensor that also further abstracts a player's

body movements. Tangibility, in the case of BDC, is more about creating an intuitive

controller rather than creating a strong link to the virtual environment.

Designing Interventions

The interventions designed for each project are similar in that they both create a task that

must be performed using the system, which is intended to engage spatial cognition.

However, they each take a slightly different approach. The teapot touching game in BDC

intends to continuously engage mental rotation by having a player perform the same task

for several minutes while the environment changes. The intervention designed for TASC

is more of a puzzle that requires the use of perspective taking skills to solve. The

differences between the interventions are partially due to the differences between the

interfaces. The puppet controller built for the BDC project focused on body movement.

Coupling that controller with a third person perspective made it possible to continuously

act in a constantly changing environment. The first person point of view used in the TASC system lends itself to a more discreet type of interaction, because only certain parts of the environment are visible from any given perspective.

The similarities and differences between these systems highlight two main points:

- System design is holistic. The ways systems establish embodiment and the interventions they support influence each other and are influenced by the context in which the systems are designed.
- The design process described in this dissertation can be applied to the design of diverse systems that engage spatial cognition through embodiment.

CHAPTER 7
CONCLUSION

This dissertation has presented research that highlights the link between the human body, action, and cognition of space and shown that the field of tangible and embodied interaction is well-suited to take advantage of that link for the purposes of creating interfaces and applications that leverage embodiment to engage, support and augment spatial cognition. Figure 37 illustrates the specific ways that TEIs engage spatial cognition based on how they establish embodiment and the sort of intervention that they present. These links between spatial cognition and embodied interaction were then used to develop a set of design guidelines, which describe how to determine an appropriate way to establish embodiment and how to design an intervention that focuses on some aspect of spatial cognition given a particular set of goals and constraints. The application of these guidelines to the design of TEI system is then illustrated through two case studies: BDC and TASC.

Contributions

While space has played an important part in digital media theory up to this point, many digital media scholars have called for research that shows how spatial cognition and embodiment can be leveraged for the design of digital systems. The discussions about digital media and space led to the formation of the following research question:

> How are the various aspects of spatial cognition and the design of tangible and embodied interfaces linked through embodiment?

To answer that research question, I made the following contributions to the field of digital media:

1. A spatial cognition based critique of previous TEI systems, showing how TEI has previously incorporated spatial cognition in support of task completion and interaction design.

In Chapter 4, I show how several previous TEI systems engage spatial cognition at the figural, vista, and environmental scale. Each system establishes embodiment in a particular way and includes a task, action, or intervention that links that style of embodiment to some aspect of spatial cognition.

2. A framework that describes how TEI systems establish embodiment and engage spatial cognition based on the scale and the content of the interaction.

Based on the critique of TEIs in Chapter 4, I developed the framework shown in Figure 20, which shows how different ways to establish embodiment at different scales can be leveraged through interventions to engage different aspects of spatial cognition. Figure 20 defines the design space of TEIs which focus on engaging spatial cognition and highlights design trends and opportunities for future work in this space.

3. A set of guidelines for designing TEI systems that establish embodiment based on aspects of spatial cognition.

Embodied interaction research has frequently invoked phenomenology when discussing the ways that tangible interaction leads to an embodied experience. Through the lens of spatial cognition, I have provided a set of guidelines for designers to determine which methods of establishing embodiment might be most appropriate for accomplishing their design goals.

4. A set of guidelines for designing digital media interventions that engage, support, or augment spatial cognition.

Space and digital media have previously been linked through virtual environments, graphical user interfaces, infographics, and network architecture. Each of these elements of digital media applies spatial cognition to improve usability, narrative immersion, or navigation. Extending the role of digital media to directly engage, support, or alter spatial cognition is another way to approach the design of digital media systems. The guidelines I present in Chapter 4 provide digital media designers with a tool for approaching the design of interventions that aim to augment human cognition.

5. A set of criteria for the evaluation of TEI systems that establish embodiment and engage spatial cognition.

Because the relationship between spatial cognition and embodiment in digital media systems is so intertwined, systems that attempt to engage spatial cognition must be evaluated in multiple ways. Separating the evaluation of embodiment from the effect on spatial cognition is important to make sure that researchers not only understand what effect a system is having, but also why it has that particular effect. Designing systems that are flexible enough to be evaluated in this way is an important consideration when conducting research based on the contributions of this dissertation.

Furthermore, by following a research trajectory that draws from the cognitive sciences to inform system design and evaluation, this work can lead to contributions to embodied cognition research as well. Separately evaluating the embodied aspects of the systems and the interventions the system supports can lead to a thorough understanding of the ways the systems establish embodiment and remove confounding variables from the intervention designs. By designing systems that can be shown to firmly establish

embodiment in known ways and that control for different variables, evaluating the systems for their effect on aspects of spatial cognition can definitively show how these design decisions impact cognition. The BDC project has already made contributions to the cognitive sciences in this way. Specifically, by conducting a mixed design experiment of mental rotation skills, BDC showed the designing interactive systems from a cognition-based perspective can alter mental rotation ability, and because of the design process it followed led to an understanding of the aspects of the design that created that effect. Because of its relationship to this research approach, TASC stands to make a similar contribution as it moves from the design phase in to evaluation.

Future Work

While this research lays the groundwork for designing systems that engage spatial cognition, many of the specifics related to the impacts of interaction design and embodiment on spatial cognition are yet to be researched. The TASC project is ongoing and will include three more phases of design, development and evaluation. There are also possibilities for similar projects based on this research that investigate the relationship between embodiment, interaction design and spatial cognition as it impacts different types of problem solving and sociocultural experiences.

With a flexible system in hand, the TASC project will continue through three major phases towards its goal of supporting STEM problem solving: evaluating embodiment, designing and evaluating additional interventions, and evaluating the practical issues related to its use in educational settings. Evaluating the embodied aspects of the current system will lead to a better understanding of the role of tangibility, head tracking, and the visualization of hand movements.

The TASC system employs each of these elements together in an attempt to induce a very strong sense of embodiment. By removing one or more of these aspects of the system and asking research participants to complete a task, researchers can show whether any of the aspects have a relatively large or small effect on embodiment. The results from that research will help researchers design future systems and interventions that rely on interactions that engage the strongest ways to create embodiment.

As the system design stabilizes, evaluating the impact of different interventions on spatial skills will yield further evidence that digital media and embodied interaction can influence spatial skills. These evaluations will follow the mixed-design described above. Because of its flexible design, future interventions developed for the TASC system may be evaluated to show effects on spatial skills other than perspective taking. Broadening the set of spatial skills being evaluated will lead to insights about which design decisions are most important for supporting spatial skills generally, which designs work for particular spatial skills, and will highlight any design decisions that reduce the effect on spatial skills.

Because of its broader goal of supporting spatial skills to improve STEM education, the TASC system will also be evaluated based on how well it can be incorporated in to education. This is a continuous process that involves iterative refinement and evaluation. Researchers held an early workshop with teachers to determine possible pain points and opportunities for the design of similar systems, the results of which are still under review. Based on the results of the workshop and the early evaluations of the perspective taking intervention, researchers will refine the system and intervention designs to better target the needs of teachers and students of STEM subjects.

Beyond TASC, extensions to this research will focus on its applicability outside of STEM education. The first of these studies may focus on the sorts of higher order cognitive skills, like time and metaphorical reasoning, which seem to be impacted by body movement and perception, both of which are related to spatial cognition, as described in the above chapters. The framework presented in Chapter 4 and the methods of establishing embodiment and designing interventions provide a clear path for designs that create the kinds of relationships between the body, space, and thought that researchers like Boroditsky and Lakoff and Johnson have uncovered.

Broader Impacts

Future research using the TASC system and showing the application of digital media to spatial cognition and to higher-level cognition may lead to several broader impacts in STEM education, embodied cognition research, tangible and embodied interaction design, and artificial intelligence.

The TASC project will lead to an early set of prototypes that have been shown to impact spatial abilities. Beyond TASC, investigating the long term impact of using similar systems on STEM learning may lead to a new paradigm for the use of digital media in educational contexts. Digital media for education currently tends to focus on specific learning goals, e.g. what is a "for loop" in computer science, or how to multiply large numbers. These digital media systems have been useful for certain types of students; however, it is possible that digital media has not yet reached its full potential with respect to education. Focusing on the ways that digital media can alter cognition may lead to new ways to engage students and support different learning styles.

Cognitive science research often relies on putting research subjects in novel situations and observes their reactions, or attempts to show the effect of that situation on a particular behavior. Understanding how embodiment is established in digital media systems and how to leverage embodiment and spatial cognition to create these sorts of novel situations may give cognitive scientists more flexibility with respect to what kinds of questions they are able to answer. For example, the BDC project showed that the common coding effect extended to physical objects that translate movement to a virtual character. In-progress research is attempting to show that tool appropriation effects also extend from virtual interactions. The knowledge that embodiment extends to virtual spaces can be leveraged to create situations which draw out subtle cognitive effects based on environmental variables that could not be previously manipulated.

As digital technology becomes part of more and more of the objects in our everyday lives, understanding the relationships between cognition of space and interaction design may lead to better designs for Internet of Things (IoT) devices. IoT devices often bridge several aspects of our lives. For example, home security systems will soon allow us to lock and unlock our houses for service workers. While managing remote access may work well enough with a button on a touch screen, the constant connection to remote places and things that IoT enables creates a different sort of space, whether it intends to or not. Understanding spatial cognition as it relates to virtual content and the body may help researchers understand the users of complex IoT systems. These networks of places and objects themselves may require embodied, spatial interfaces for people to be able to effectively manage them.

Finally, with the recent defeat of the world GO champion by Google's AlphaGo artificial intelligence (AI) program, AI stands to become viable much faster than many people predicted. However, AI research still tends to investigate cognition and embodiment separately. Understanding how humans leverage their motor systems to perform higher order cognition may lead to insights about how to combine thinking machines and doing machines, and may create a new paradigm for a holistic, embodied model of artificial intelligence. The research presented in this dissertation provides a foundation for future work that leverages digital media and interaction design to better understand the mind-body relationship, which is very important for the ultimate blending of digital media with our day to day lives.

BIBLIOGRAPHY

1. Allen, Gary L., Kathleen C. Kirasic, Shannon H. Dobson, Richard G. Long, and Sharon Beck. 1996. "Predicting Environmental Learning from Spatial Abilities: An Indirect Route." *Intelligence* 22 (3): 327–55. doi:10.1016/S0160-2896(96)90026-4.

2. Antle, Alissa N., and Sijie Wang. 2013. "Comparing Motor-Cognitive Strategies for Spatial Problem Solving with Tangible and Multi-Touch Interfaces." In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, 65–72. TEI '13. New York, NY, USA: ACM. doi:10.1145/2460625.2460635.

3. Avraamides, Marios N., Jack M. Loomis, Roberta L. Klatzky, and Reginald G. Golledge. 2004. "Functional Equivalence of Spatial Representations Derived From Vision and Language: Evidence From Allocentric Judgments." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 30 (4): 801–14. doi:10.1037/0278-7393.30.4.804.

4. Beardsworth, T., and T. Buckner. 1981. "The Ability to Recognize Oneself from a Video Recording of One's Movements without Seeing One's Body." *Bulletin of the Psychonomic Society* 18 (1): 19–22.

5. Benedikt, Michael. 1991. *Cyberspace : First Steps*. Cambridge Mass.: MIT Press.

6. Bhalla, Mukul, and Dennis R. Proffitt. 1999. "Visual–motor Recalibration in Geographical Slant Perception." *Journal of Experimental Psychology: Human Perception and Performance* 25 (4): 1076–96. doi:10.1037/0096-1523.25.4.1076.

7. Bloom, Paul. 1999. *Language and Space*. MIT Press.

8. Bonifazi, S., A. Farnè, L. Rinaldesi, and E. Làdavas. 2007. "Dynamic Size-Change of Peri-Hand Space through Tool-Use: Spatial Extension or Shift of the Multi-Sensory Area." *Journal of Neuropsychology* 1 (1): 101–14. doi:10.1348/174866407X180846.

9. Boroditsky, Lera. 2000. "Metaphoric Structuring: Understanding Time through Spatial Metaphors." *Cognition* 75 (1): 1–28. doi:10.1016/S0010-0277(99)00073-6.

10. Boroditsky, Lera, and Michael Ramscar. 2002. "The Roles of Body and Mind in Abstract Thought." *Psychological Science* 13 (2): 185–89. doi:10.1111/1467-9280.00434.

11. Burte, Heather, and Mary Hegarty. 2012. "Revisiting the Relationship between Allocentric-Heading Recall and Self-Reported Sense of Direction." In *Proceedings of the 34th Annual Conference of the Cognitive Science Society*, 162–67.

12. Carlson, L.A., and R. Kenny. 2005. "Constraints on Spatial Language Comprehension: Function and Geometry." In *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thinking*, edited by D. Pecher and R.A. Zwann, 35–64. Cambridge: Cambridge University Press.

13. Casasanto, Daniel, Olga Fotakopoulou, and Lera Boroditsky. 2010. "Space and Time in the Child S Mind: Evidence for a Cross-Dimensional Asymmetry." *Cognitive Science* 34 (3): 387–405. doi:10.1111/j.1551-6709.2010.01094.x.

14. Chandrasekharan, Sanjay, Dilip Athreya, and Narayanan Srinivasan. 2006. "Twists and Oliver Twists in Mental Rotation: Complementary Actions as Orphan Processes." In *Proceedings of the 28th Annual Conference of the Cognitive Science Society, Vancouver, Sheridan*, 1092–97.

15. Clark, Andy. 1997. "Being There Putting Brain, Body, and World Together Again /."

16. Cohen, Cheryl A., and Mary Hegarty. 2007. "Sources of Difficulty in Imagining Cross Sections of 3D Objects." In *Proceedings of the Twenty-Ninth Annual Conference of the Cognitive Science Society*, 179–84. http://groups.psych.northwestern.edu/uttal/people/documents/CCohen_Sources ofdifficultyinimaginingcrosssectionsof3Dobjects.pdf.

17. Cooper, Seth, Firas Khatib, Adrien Treuille, Janos Barbero, Jeehyung Lee, Michael Beenen, Andrew Leaver-Fay, David Baker, Zoran Popović, and Foldit Players. 2010. "Predicting Protein Structures with a Multiplayer Online Game." *Nature* 466 (7307): 756–60. doi:10.1038/nature09304.

18. Costantini, Marcello, Ettore Ambrosini, Corrado Sinigaglia, and Vittorio Gallese. 2011. "Tool-Use Observation Makes Far Objects Ready-to-Hand." *Neuropsychologia* 49 (9): 2658–63. doi:10.1016/j.neuropsychologia.2011.05.013.

19. Crawford, Hugh. 2015. "Thinking Hot: Risk, Prehension, and Sympathy in Design." In *Deleuze and Design*, edited by Betti Marenko and Jamie Brassett. Deleuze Connections. Edinburgh: Edinburgh University Press. http://bibdata.princeton.edu/bibliographic/9139621.

20. Cutting, James E., and Lynn T. Kozlowski. 1977. "Recognizing Friends by Their Walk: Gait Perception without Familiarity Cues." *Bulletin of the Psychonomic Society* 9 (5): 353–56.

21. Darken, Rudolph P., David Bernatovich, John P. Lawson, and Barry Peterson. 1999. "Quantitative Measures of Presence in Virtual Environments: The Roles of Attention and Spatial Comprehension." *CyberPsychology & Behavior* 2 (4): 337–47. doi:10.1089/cpb.1999.2.337.

22. Denis, Michel, and Jack M. Loomis. 2006. "Perspectives on Human Spatial Cognition: Memory, Navigation, and Environmental Learning." *Psychological Research* 71 (3): 235–39. doi:10.1007/s00426-006-0079-x.

23. Dourish, Paul. 2004. *Where The Action Is: The Foundations Of Embodied Interaction*. MIT Press.

24. Dreyfus, Hubert L. 2012. "The Current Relevance of Merleau-Ponty's Phenomenology of Embodiment." Accessed December 18. http://ejap.louisiana.edu/ejap/1996.spring/dreyfus.1996.spring.html.

25. Fernaeus, Ylva, Jakob Tholander, and Martin Jonsson. 2008a. "Towards a New Set of Ideals: Consequences of the Practice Turn in Tangible Interaction." In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, 223–30. TEI '08. New York, NY, USA: ACM. doi:10.1145/1347390.1347441.

26. ———. 2008b. "Beyond Representations: Towards an Action-Centric Perspective on Tangible Interaction." *International Journal of Arts and Technology* 1 (3): 249–67. doi:10.1504/IJART.2008.022362.

27. Firestone, Chaz. 2013. "How 'Paternalistic' Is Spatial Perception? Why Wearing a Heavy Backpack Doesn't—and Couldn't—Make Hills Look Steeper." *Perspectives on Psychological Science* 8 (4): 455–73. doi:10.1177/1745691613489835.

28. Fischer, Patrick Tobias, Eva Hornecker, and Christian Zoellner. 2013. "SMSlingshot: An Expert Amateur DIY Case Study." In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, 9–16. TEI '13. New York, NY, USA: ACM. doi:10.1145/2460625.2460627.

29. Fishkin, Kenneth P. 2004. "A Taxonomy for and Analysis of Tangible Interfaces." *Personal and Ubiquitous Computing* 8 (5): 347–58. doi:10.1007/s00779-004-0297-4.

30. Fitzmaurice, George W., Hiroshi Ishii, and William A. S. Buxton. 1995. "Bricks: Laying the Foundations for Graspable User Interfaces." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 442–49. CHI '95. New York, NY, USA: ACM Press/Addison-Wesley Publishing Co. doi:10.1145/223904.223964.

31. Frick, Andrea, Wenke Möhring, and Nora S. Newcombe. 2014. "Picturing Perspectives: Development of Perspective-Taking Abilities in 4- to 8-Year-Olds." *Developmental Psychology* 5: 386. doi:10.3389/fpsyg.2014.00386.

32. Frick, Andrea, and Nora S. Newcombe. 2012. "Getting the Big Picture: Development of Spatial Scaling Abilities." *Cognitive Development* 27 (3): 270–82. doi:10.1016/j.cogdev.2012.05.004.

33. Gibson, William. 2000. *Neuromancer*. Penguin.

34. Golledge, Reginald G. 1999. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. JHU Press.

35. Graetz, J. Martin. 1981. "The Origin of Spacewar." *Creative Computing* 18.

36. Harris, Justin. 2014. "Where Will It Go? Concepts of Motion in Complex Events." TEMPLE UNIVERSITY. http://gradworks.umi.com/36/11/3611138.html.

37. Hegarty, Mary, Daniel R. Montello, Anthony E. Richardson, Toru Ishikawa, and Kristin Lovelace. 2006. "Spatial Abilities at Different Scales: Individual Differences in Aptitude-Test Performance and Spatial-Layout Learning." *Intelligence* 34 (2): 151–76. doi:10.1016/j.intell.2005.09.005.

38. Hegarty, Mary, Anthony E Richardson, Daniel R Montello, Kristin Lovelace, and Ilavanil Subbiah. 2002. "Development of a Self-Report Measure of Environmental Spatial Ability." *Intelligence* 30 (5): 425–47. doi:10.1016/S0160-2896(02)00116-2.

39. Hegarty, Mary, and David Waller. 2004. "A Dissociation between Mental Rotation and Perspective-Taking Spatial Abilities." *Intelligence* 32 (2): 175–91. doi:10.1016/j.intell.2003.12.001.

40. Hickmann, Maya, and Stéphane Robert. 2006. *Space in Languages: Linguistic Systems and Cognitive Categories*. John Benjamins Publishing.

41. Hornecker, Eva, and Jacob Buur. 2006. "Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 437–46. CHI '06. New York, NY, USA: ACM. doi:10.1145/1124772.1124838.

42. Hurley, Susan. 2001. "Perception And Action: Alternative Views." *Synthese* 129 (1): 3–40. doi:10.1023/A:1012643006930.

43. Huttenlocher, J., N. Newcombe, and E. H. Sandberg. 1994. "The Coding of Spatial Location in Young Children." *Cognitive Psychology* 27 (2): 115–47. doi:10.1006/cogp.1994.1014.

44.   Iriki, A., M. Tanaka, and Y. Iwamura. 1996. "Coding of Modified Body Schema during Tool Use by Macaque Postcentral Neurones." *Neuroreport* 7 (14): 2325–30.

45.   Iriki, Atsushi, Michio Tanaka, Shigeru Obayashi, and Yoshiaki Iwamura. 2001. "Self-Images in the Video Monitor Coded by Monkey Intraparietal Neurons." *Neurosci. Res.* 40 (2): 163–73.

46.   Ishii, Hiroshi, and Brygg Ullmer. 1997. "Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms." In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, 234–41. CHI '97. New York, NY, USA: ACM. doi:10.1145/258549.258715.

47.   Ishii, Hiroshi, Craig Wisneski, Julian Orbanes, Ben Chun, and Joe Paradiso. 1999. "PingPongPlus: Design of an Athletic-Tangible Interface for Computer-Supported Cooperative Play." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 394–401. CHI '99. New York, NY, USA: ACM. doi:10.1145/302979.303115.

48.   Jovanov, Kimberley, Paul Clifton, Ali Mazalek, Michael Nitsche, and Timothy N. Welsh. 2015. "The Limb-Specific Embodiment of a Tool Following Experience." *Experimental Brain Research* 233 (9): 2685–94. doi:10.1007/s00221-015-4342-5.

49.   Kao, Kai-Ling C., and Melvyn A. Goodale. 2009. "Enhanced Detection of Visual Targets on the Hand and Familiar Tools." *Neuropsychologia* 47 (12): 2454–63. doi:10.1016/j.neuropsychologia.2009.04.016.

50.   Kim, Mi Jeong, and Mary Lou Maher. 2008. "The Impact of Tangible User Interfaces on Designers' Spatial Cognition." *Human–Computer Interaction* 23 (2): 101–37. doi:10.1080/07370020802016415.

51.   Kirsh, David. 1995. "Complementary Strategies: Why We Use Our Hands When We Think." In *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society*, 212–17. http://books.google.com/books?hl=en&lr=&id=Y5XdpTwv1f0C&oi=fnd&pg=PA212&dq=kirsh+complementary+strategies&ots=7vQgWfNCZS&sig=F492D1c8CowpGhB4Vl_aImKUcDs.

52.   Klatzky, Roberta L. 1998. "Allocentric and Egocentric Spatial Representations: Definitions, Distinctions, and Interconnections." In *Spatial Cognition*, edited by Christian Freksa, Christopher Habel, and Karl F. Wender, 1–17. Lecture Notes in Computer Science 1404. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/3-540-69342-4_1.

53.   Klemmer, Scott R., Björn Hartmann, and Leila Takayama. 2006. "How Bodies Matter: Five Themes for Interaction Design." In *Proceedings of the 6th*

Conference on Designing Interactive Systems, 140–49. DIS '06. New York, NY, USA: ACM. doi:10.1145/1142405.1142429.

54.   Kontra, Carly, Daniel J. Lyons, Susan M. Fischer, and Sian L. Beilock. 2015. "Physical Experience Enhances Science Learning." *Psychological Science* 26 (6): 737–49.

55.   Kortemeyer, Gerd, Philip Tan, and Steven Schirra. 2013. "A Slower Speed of Light: Developing Intuition about Special Relativity with Games." In *Proceedings of the International Conference on the Foundations of Digital Games (FDC '13)*, 400–402. New York, NY: ACM. http://www.fdg2013.org/program/festival/openrelativity.pdf.

56.   Laguna, Canary Island Manuel de Vega Professor of Cognitive Psychology Universidad de La, Margaret Jean Intons-Peterson Professor of Cognitive Psychology Indiana University, Philip N. Johnson-Laird Professor of Cognitive Psychology Indiana University, Michel Denis Professor of Cognitive Psychology Indiana University, and Teaching and Learning Marc Marschark Director of the Center for Research of Technology. 1996. *Models of Visuospatial Cognition*. Oxford University Press.

57.   Landau, Deb Miller. 2016. "3D Facial Projection Technology Creates Digital Skin." *iQ by Intel*. February 16. https://iq.intel.com/artist-uses-3d-facial-projection-technology-to-create-digital-makeup/.

58.   Liben, Lynn S., and Roger M. Downs. 1994. "Fostering Geographic Literacy from Early Childhood: The Contributions of Interdisciplinary Research." *Journal of Applied Developmental Psychology* 15 (4): 549–69. doi:10.1016/0193-3973(94)90022-1.

59.   Lozano, Sandra C., Bridgette Martin Hard, and Barbara Tversky. 2007. "Putting Action in Perspective." *Cognition* 103 (3): 480–90. doi:10.1016/j.cognition.2006.04.010.

60.   Lubinski, David, and Camilla Persson Benbow. 2006. "Study of Mathematically Precocious Youth After 35 Years: Uncovering Antecedents for the Development of Math-Science Expertise." *Perspectives on Psychological Science* 1 (4): 316–45. doi:10.1111/j.1745-6916.2006.00019.x.

61.   Maravita, Angelo, Charles Spence, Steffan Kennett, and Jon Driver. 2002. "Tool-Use Changes Multimodal Spatial Interactions between Vision and Touch in Normal Humans." *Cognition* 83 (2): B25–34. doi:10.1016/S0010-0277(02)00003-3.

62.   May, Mark. 2004. "Imaginal Perspective Switches in Remembered Environments: Transformation versus Interference Accounts." *Cognitive Psychology* 48 (2): 163–206. doi:10.1016/S0010-0285(03)00127-0.

63.	Mazalek, Ali, Sanjay Chandrasekharan, Michael Nitsche, Tim Welsh, Paul Clifton, Andrew Quitmeyer, Firaz Peer, Friedrich Kirschner, and Dilip Athreya. 2011. "I'm in the Game: Embodied Puppet Interface Improves Avatar Control." In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*, 129–36. TEI '11. New York, NY, USA: ACM. doi:10.1145/1935701.1935727.

64.	Mazalek, Ali, Sanjay Chandrasekharan, Michael Nitsche, Tim Welsh, Geoff Thomas, Tandav Sanka, and Paul Clifton. 2009. "Giving Your Self to the Game: Transferring a Player's Own Movements to Avatars Using Tangible Interfaces." In *Proceedings of the 2009 ACM SIGGRAPH Symposium on Video Games*, 161–68. Sandbox '09. New York, NY, USA: ACM. doi:10.1145/1581073.1581098.

65.	Mazalek, Ali, and Michael Nitsche. 2007. "Tangible Interfaces for Real-Time 3D Virtual Environments." In *Proceedings of the International Conference on Advances in Computer Entertainment Technology*, 155–62. ACE '07. New York, NY, USA: ACM. doi:10.1145/1255047.1255080.

66.	Mazalek, Ali, Michael Nitsche, Sanjay Chandrasekharan, Tim Welsh, Paul Clifton, Andrew Quitmeyer, Firaz Peer, and Friedrich Kirschner. 2010. "Recognizing Self in Puppet Controlled Virtual Avatars." In *Proceedings of the 3rd International Conference on Fun and Games*, 66–73. Fun and Games '10. New York, NY, USA: ACM. doi:10.1145/1823818.1823825.

67.	Mazalek, Ali, and Elise van den Hoven. 2009. "Framing Tangible Interaction Frameworks." *AI EDAM* 23 (Special Issue 03): 225–35. doi:10.1017/S0890060409000201.

68.	Merleau-Ponty, Maurice. 1996. *Phenomenology Of Perception*. Motilal Banarsidass Publishe.

69.	Mohler, James L. 2008. "The Impact of Visualization Methodology on Spatial Problem Solutions Among High and Low Visual Achievers." *Journal of Industrial Technology* 24 (1): 1–9.

70.	Montello, Daniel R. 1993. "Scale and Multiple Psychologies of Space." In *Spatial Information Theory A Theoretical Basis for GIS*, edited by Andrew U. Frank and Irene Campari, 312–21. Lecture Notes in Computer Science 716. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/3-540-57207-4_21.

71.	Morsella, Ezequiel, and Robert M. Krauss. 2004. "The Role of Gestures in Spatial Working Memory and Speech." *The American Journal of Psychology* 117 (3): 411–24. doi:10.2307/4149008.

72.	Mou, Weimin, Timothy P. McNamara, Christine M. Valiquette, and Björn Rump. 2004. "Allocentric and Egocentric Updating of Spatial Memories."

Journal of Experimental Psychology: Learning, Memory, and Cognition 30 (1): 142–57. doi:10.1037/0278-7393.30.1.142.

73.   Murray, Janet. 1997. *Hamlet on the Holodeck: The Future of Narrative in Cyberspace*. Cambridge: The MIT Press.

74.   ———. 2011. *Inventing the Medium: Principles of Interaction Design As a Cultural Practice*. The MIT Press.

75.   Mylov, Peer. 2002. "Virtual Space." In , edited by Lars Qvortrup, 47–70. London, UK, UK: Springer-Verlag. http://dl.acm.org/citation.cfm?id=778632.778637.

76.   Nagel, Saskia K, Christine Carl, Tobias Kringe, Robert Märtin, and Peter König. 2005. "Beyond Sensory Substitution—learning the Sixth Sense." *Journal of Neural Engineering* 2 (4): R13–26. doi:10.1088/1741-2560/2/4/R02.

77.   Newcombe, N. S., and T. F. Shipley. 2013. "Thinking about Spatial Thinking: New Typology, New Assessments." *Studying Visual and Spatial Reasoning for Design Creativity. New York, NY: Springer*. Accessed January 8. http://mason.gmu.edu/~jgero/conferences/sdc10/papers/Newcombe.pdf.

78.   Nitsche, Michael. 2008. *Video Game Spaces : Image, Play, and Structure in 3D Game Worlds*. Cambridge Mass.: MIT Press.

79.   Peters, Michael, and Christian Battista. 2008. "Applications of Mental Rotation Figures of the Shepard and Metzler Type and Description of a Mental Rotation Stimulus Library." *Brain and Cognition* 66 (3): 260–64. doi:10.1016/j.bandc.2007.09.003.

80.   Peters, M., B. Laeng, K. Latham, M. Jackson, R. Zaiyouna, and C. Richardson. 1995. "A Redrawn Vandenberg and Kuse Mental Rotations Test - Different Versions and Factors That Affect Performance." *Brain and Cognition* 28 (1): 39–58. doi:10.1006/brcg.1995.1032.

81.   Piaget, Jean, and Barbel Inhelder. 1967. *The Child's Conception of Space*. Translated by F. J. Langdon and J. L. Lunzer. New York: W. W. Norton & Company.

82.   "PingPongPlus CHI Video 1999 on Vimeo." 2016. Accessed April 7. https://vimeo.com/48835482.

83.   Portugali, Juval. 1996. *The Construction of Cognitive Maps*. Springer Science & Business Media.

84.   Poynor, Rick. 1995. "The Hand That Rocks the Cradle: Gillian Crampton Smith Is Making the Royal College of Art's Computer Related Design

Program a Multimedia Powerhouse." *ID-NEW YORK-DESIGN PUBLICATIONS*- 42: 60–60.

85. Previc, F. H. 1998. "The Neuropsychology of 3-D Space." *Psychological Bulletin* 124 (2): 123–64.

86. Prinz, Wolfgang. 2005. "An Ideomotor Approach to Imitation." In *Perspectives on Imitation: From Neuroscience to Social Science: Vol. 1: Mechanisms of Imitation and Imitation in Animals*, edited by S. Hurley and N. Chater, 141–56. Cambridge, MA, US: MIT Press.

87. Proffitt, Dennis R. 2013. "An Embodied Approach to Perception By What Units Are Visual Perceptions Scaled?" *Perspectives on Psychological Science* 8 (4): 474–83. doi:10.1177/1745691613489837.

88. Proffitt, Dennis R., Jeanine Stefanucci, Tom Banton, and William Epstein. 2003. "The Role of Effort in Perceiving Distance." *Psychological Science* 14 (2): 106–12. doi:10.1111/1467-9280.t01-1-01427.

89. Proffitt, DR, and SA Linkenauger. 2013. "Perception Viewed as a Phenotypic Expression." In *Action Science: Foundations of an Emerging Discipline*, edited by Prinz, W., M. Beisert, and A. Herwig, 171–98. Cambridge, MA, USA: MIT Press. https://mitpress.mit.edu/books/action-science.

90. Quarles, J., S. Lampotang, I. Fischler, P. Fishwick, and B. Lok. 2008. "Tangible User Interfaces Compensate for Low Spatial Cognition." In *IEEE Symposium on 3D User Interfaces, 2008. 3DUI 2008*, 11–18. doi:10.1109/3DUI.2008.4476585.

91. Raffle, Hayes Solos, Amanda J. Parkes, and Hiroshi Ishii. 2004. "Topobo: A Constructive Assembly System with Kinetic Memory." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 647–54. CHI '04. New York, NY, USA: ACM. doi:10.1145/985692.985774.

92. Shaer, Orit, and Eva Hornecker. 2010. "Tangible User Interfaces: Past, Present, and Future Directions." *Found. Trends Hum.-Comput. Interact.* 3 (1–2): 1–137. doi:10.1561/1100000026.

93. Sharlin, Ehud, Benjamin Watson, Yoshifumi Kitamura, Fumio Kishino, and Yuichi Itoh. 2004. "On Tangible User Interfaces, Humans and Spatiality." *Personal Ubiquitous Comput.* 8 (5): 338–46. doi:10.1007/s00779-004-0296-5.

94. Shea, Daniel L., David Lubinski, and Camilla P. Benbow. 2001. "Importance of Assessing Spatial Ability in Intellectually Talented Young Adolescents: A 20-Year Longitudinal Study." *Journal of Educational Psychology* 93 (3): 604–14. doi:10.1037/0022-0663.93.3.604.

95.   Shepard, Roger N., and Lynn A. Cooper. 1986. *Mental Images and Their Transformations*. Vol. viii. Cambridge, MA, US: The MIT Press.

96.   "Sony Realtime Projection Mapping 1 on Vimeo." 2016. Accessed April 7. https://vimeo.com/34021153.

97.   SRI International. 1968. *1968 Demo - FJCC Conference Presentation Reel #1*. http://archive.org/details/XD300-23_68HighlightsAResearchCntAugHumanIntellect.

98.   Super, Donald E., and Paul B. Bachrach. 1957. *Scientific Careers and Vocational Development Theory: A Review, a Critique and Some Recommendations*. Vol. xii. Oxford, England: Columbia Univer.

99.   Sutherland, Ivan E. 1964. "Sketch Pad a Man-Machine Graphical Communication System." In *Proceedings of the SHARE Design Automation Workshop*, 6.329–6.346. ACM.

100. Taylor, Eric T., Jessica K. Witt, and Phillip J. Grimaldi. 2012. "Uncovering the Connection between Artist and Audience: Viewing Painted Brushstrokes Evokes Corresponding Action Representations in the Observer." *Cognition* 125 (1): 26–36. doi:10.1016/j.cognition.2012.06.012.

101. Taylor, Holly A, and Barbara Tversky. 1992. "Spatial Mental Models Derived from Survey and Route Descriptions." *Journal of Memory and Language* 31 (2): 261–92. doi:10.1016/0749-596X(92)90014-O.

102. Taylor, J. Eric T., Jessica K. Witt, and Mila Sugovic. 2011. "When Walls Are No Longer Barriers: Perception of Wall Height in Parkour." *Perception* 40 (6): 757–60. doi:10.1068/p6855.

103. "TheMacula - The 600 Years, Astronomical Clock Tower, Prague." 2016. *INITI*. Accessed March 25. http://www.initi.org/workss/600-years/.

104. Trofatter, Caroline, Carly Kontra, Sian Beilock, and Susan Goldin-Meadow. 2015. "Gesturing Has a Larger Impact on Problem-Solving than Action, Even When Action Is Accompanied by Words." *Language, Cognition and Neuroscience* 30 (3): 251–60.

105. Tversky, Barbara. 2000. "Some Ways That Maps and Diagrams Communicate." In *Spatial Cognition II*, edited by Christian Freksa, Christopher Habel, Wilfried Brauer, and Karl F. Wender, 72–79. Lecture Notes in Computer Science 1849. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/3-540-45460-8_6.

106. ———. 2002. "Navigating by Mind and by Body." In *Spatial Cognition III*, edited by Christian Freksa, Wilfried Brauer, Christopher Habel, and Karl F.

Wender, 1–10. Lecture Notes in Computer Science 2685. Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/3-540-45004-1_1.

107. Tversky, Barbara, and Bridgette Martin Hard. 2009. "Embodied and Disembodied Cognition: Spatial Perspective-Taking." *Cognition* 110 (1): 124–29. doi:10.1016/j.cognition.2008.10.008.

108. Ullmer, B., and H. Ishii. 2000. "Emerging Frameworks for Tangible User Interfaces." *IBM Systems Journal* 39 (3.4): 915–31. doi:10.1147/sj.393.0915.

109. Underkoffler, John, and Hiroshi Ishii. 1999. "Urp: A Luminous-Tangible Workbench for Urban Planning and Design." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 386–93. CHI '99. New York, NY, USA: ACM. doi:10.1145/302979.303114.

110. Uttal, David H. 2000. "Seeing the Big Picture: Map Use and the Development of Spatial Cognition." *Developmental Science* 3 (3): 247–64. doi:10.1111/1467-7687.00119.

111. Uttal, David H., Nathaniel G. Meadow, Elizabeth Tipton, Linda L. Hand, Alison R. Alden, Christopher Warren, and Nora S. Newcombe. 2013. "The Malleability of Spatial Skills: A Meta-Analysis of Training Studies." *Psychological Bulletin* 139 (2): 352–402. doi:10.1037/a0028446.

112. Vaishnavi, S., J. Calhoun, and A. Chatterjee. 2001. "Binding Personal and Peripersonal Space: Evidence from Tactile Extinction." *Journal of Cognitive Neuroscience* 13 (2): 181–89. doi:10.1162/089892901564243.

113. van der Hoort, B., A. Guterstam, and H. Ehrsson. 2011. "Being Barbie: The Size of One's Own Body Determines the Perceived Size of the World." *PLoS ONE* 6 (5): 0. doi:10.1371/journal.pone.0020195.

114. van Dijk, Jelle. 2013. "Creating Traces, Sharing Insight: Explorations in Embodied Cognition Design." Technische Universiteit Eindhoven.

115. van Dijk, Jelle, Remko van der Lugt, and Caroline Hummels. 2013. "Beyond Distributed Representation: Embodied Cognition Design Supporting Socio-Sensorimotor Couplings." In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*, 181–88. TEI '14. New York, NY, USA: ACM. doi:10.1145/2540930.2540934.

116. Wai, Jonathan, David Lubinski, and Camilla P. Benbow. 2009. "Spatial Ability for STEM Domains: Aligning over 50 Years of Cumulative Psychological Knowledge Solidifies Its Importance." *Journal of Educational Psychology* 101 (4): 817–35. doi:10.1037/a0016127.

117. Webb, Rose Mary, David Lubinski, and Camilla Persson Benbow. 2007. "Spatial Ability: A Neglected Dimension in Talent Searches for Intellectually

Precocious Youth." *Journal of Educational Psychology* 99 (2): 397–420. doi:10.1037/0022-0663.99.2.397.

118. Weiser, Mark. 1999. "The Computer for the 21st Century." *SIGMOBILE Mob. Comput. Commun. Rev.* 3 (3): 3–11. doi:10.1145/329124.329126.

119. Wexler, Mark, Stephen M Kosslyn, and Alain Berthoz. 1998. "Motor Processes in Mental Rotation." *Cognition* 68 (1): 77–94. doi:10.1016/S0010-0277(98)00032-8.

120. Witt, Jessica K. 2011. "Action's Effect on Perception." *Current Directions in Psychological Science* 20 (3): 201–6. doi:10.1177/0963721411408770.

121. Witt, Jessica K., and Dennis R. Proffitt. 2005. "See the Ball, Hit the Ball Apparent Ball Size Is Correlated With Batting Average." *Psychological Science* 16 (12): 937–38. doi:10.1111/j.1467-9280.2005.01640.x.

122. Witt, Jessica K, Dennis R Proffitt, and William Epstein. 2005. "Tool Use Affects Perceived Distance, but Only When You Intend to Use It." *Journal of Experimental Psychology. Human Perception and Performance* 31 (5): 880–88. doi:10.1037/0096-1523.31.5.880.

123. Wohlschläger, Andreas. 2001. "Mental Object Rotation and the Planning of Hand Movements." *Perception & Psychophysics* 63 (4): 709–18. doi:10.3758/BF03194431.