PHYSICAL DESIGN COGNITION

An analytical study of exploratory model making to
inform creative robotic interaction

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Submitted to the Department of Architecture
In partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Architecture: Design and Computation

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ABSTRACT

In current practices of digital design fabrication, model making is bifurcated into screen based visualization (CAD) and machine based production (CAM), which limits the body's capability of generating creative thought through material interaction. If theories from the field of cognitive science about embodied cognition are true, then there is opportunity to re-think how CAD-CAM technologies can better harness the bodily based thinking involved in physical model making.

To study how designers explore ideas when making models an experiment was run in which experienced architects and novice students were asked to construct their dream house out of blocks. The hypothesis was that experienced architects would exhibit physical interactions with the blocks that distinguish them from the novices, thus helping define what may be called *physical* design cognition. To test this their behaviors were coded in terms of simple robotic actions: adding, subtracting, modifying, and relocating blocks. Architects differed from students along three dimensions. Architects were more controlled using fewer blocks overall and fewer variations; they reported more thoughts about spatial relationships and material constraints; and lastly, they more frequently experimented with multiple block positions within the model.

Together these findings suggest that architects physically explore the design space more effectively than students by exploiting body-material interactions. This designerly embodied intelligence is something that robotic technology can support and enhance. As roboticist Rodney Brooks famously said, "The world is its own best model." In other words, designers should not be limited to visualizing a model on a screen before making it physical. Implications for material-based robotic interaction are discussed and a pilot program is presented in which designers interact in real-time with a robotic manipulator arm to make physical models.

Thesis Supervisor: Lawrence Sass
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Kit

Dennis

My family

Morgan

To Mom

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CHAPTER 1

THE PHYSICAL FORM OF DESIGN THINKING

An introduction

"First learn your instrument, then learn the music, then forget all that and just play."

-Charlie Parker

1.1 What is Physical Design Cognition?

When designers want to explore new ideas they often work with their hands. They put away their computers so they can quickly sketch out concepts and diagrams and they gesture to visualize form and function. They manipulate material in hand to understand its potential and they construct physical models to see spatial relationships in three dimensions. The benefit of working with their hands is that they don't need to think much about it, they can just do it. There is little risk involved in terms of the time commitment and there is big reward in terms of the information gathered. When working with one's hands there is freedom to test and feel out ideas all with a tangible immediacy. This is different from how we work with computers. Computers require specialized training and advanced planning. One must learn the software—its interface, commands, and the language to control and produce effects on screen. You have to learn the hardware too—operating simple devices like keyboards, screens, printers, and plotters, and more recently more technical devices like 3D printers, laser cutters, and CNC machines. Why is this? What's happened to the way designers work with their hands—drawing, crafting, and model making, for example, and why can't the way we work with computers and other technologies be like that?

This question has deep roots in the study of design thinking spanning many decades and covering many fields including design computation, artificial intelligence, and human computer interaction, cognitive science, and philosophy of mind, just to name a few. In this dissertation I adopt an embodied cognitive viewpoint of design thinking; namely, I focus on the cognitive processes implemented by designers in their physical form, in the actions that designers perform. Design thinking in this sense is more than an intellectual activity or abstract process internal to the mind; it is an external bodily-based experience. This bodily based, physical kind of know-how can be thought of as a special case of design thinking. In the cognitive sciences this viewpoint is known as embodied, situated and extended forms of cognition. It is as though our thoughts flow beyond our brains throughout our bodies and out into the world.

Consider the simple example of how one might play with blocks to make a three dimensional structure. We don't need to know in advance and robotically plan out every step involved such as visually locating the objects within a field, opening up our fingers and thumb, moving our hand into place, gripping the block with the necessary force, moving the block some distance, and releasing the block at some new location and orientation. And yet, each of these steps does happen and necessarily has some impact on how we think and what we create. Furthermore, many times we don't know where we want the block to be until we see it. Going through the actions may give rise to new ideas that we wouldn't have otherwise had. How exactly is this possible? How can we do all of this without thinking about it? Certainly at some point we had to learn how to play with blocks. We had to learn that if we picked them up we could stack them and rotate them and arrange to make all sorts of structures like walls, towers, arches, and castles.

Thankfully, we don't have to think about each step involved anymore; we are free to disengage our thoughts from our actions. Or are we? What if action itself a form of thinking as claimed in cognitive science? If this is the case there must be some underlying structure because the freedom of working with our hands is seemingly boundless – how do we contain ourselves? What exactly are we thinking about when we work with our hands? What drives our thinking? How does our physical experience shape our thought processes? If we can better understand the relationship between physical action and thinking we may be able tap into this tacit kind of know-how and potentially enhance and extend our creativity.

Skilled designers are masters of containment—of providing self-imposed boundaries. They may be given a design brief at the beginning of a project but they often redefine the requirements throughout the course of its development. What are designers thinking about when engaged in physical design activity – like in their material interactions in model making activity for instance? Interestingly, their boundaries are often not known in advance. Not knowing what you're looking for until you find it requires a structure within which to think and bump up against. Perhaps an architectural designer needs to make a house with three rooms. Three blocks may be a logical starting point to explore spatial ideas, but it's hard to imagine what the blocks might look like when arranged in a particular configuration. Will the blocks balance? Will their faces align at the same angle? What will the spaces in between the blocks look like? Who knows? And why bother thinking about it – it's easier just to place them as such, move them around, and then see them. Design theorist Donald Schön called such an act a 'move experiment': manipulate the material and then see what jumps out at you as a potential solution (Schön1992). A constraint might emerge that wasn't considered beforehand. It is through physical interaction that boundaries become apparent and then useful. Sometimes brains drive thinking forward and sometimes the events happening around us drive thinking forward.

In this dissertation I explore the topic of how designers think by doing in the most literal sense. I hold the idea that there is a special kind of bodily-based thinking that happens in design activity that is driven by our physical experience and interaction with material, tools, and the spatial environment around us. This is in contrast to the idea that design thinking resides only in the brain as an intellectual activity. Certainly designers conceptualize and represent form in their minds, but there is more. It is through action in a specific environment that ideas are made real and this is critical in design thinking.

These embodied and situational processes have implications for the tools designers use to manipulate material. This claim is central to field of human-computer interaction (HCI). As Paul Dourish writes, "The topic of *context* has become a central focus for a considerable number of research investigations around the interaction between humans and computers..." and it "...is the recognition of the mutual influence of the physical environment and the human activities that unfold within it" that have led to two research topics: "These two topics are (a) physically based interaction and augmented environments and (b) attempts to develop interactive systems around understandings of the generally operative social processes surrounding everyday interaction" (pg. 230-231, 2001).

As an architectural designer I have specific views on how design processes give shape to design ideas. I believe I work best when I'm working with my hands to directly manipulate material. My interactions with material tell me things I wouldn't have gathered through thought alone. Computers, as designers use them now in most design activity, don't allow direct material engagement. Designers in a computational context are removed by the abstract representation of material on a screen. But this doesn't need to be the case.

The premise of this dissertation is that embodied design thinking is observable and measurable, if only we knew what to look for. Furthermore, there is potential to frame this embodied form of thinking in design activity in terms that a computer can process and put to use. We should seek to understand how skilled designers work in the most literally sense with material. Many questions need answering: what are their actions on it? Do their hands have different roles? How much time do they spend on a particular action? What kinds of action are possible? I call this kind of action *physical design cognition* and in this dissertation I develop a theoretical framework which attempts to reveal some of its qualities as a means to explain what goes on in a creative design process. By revealing the nature of physical design cognition we can develop new technologies to support, transfer, and extend this knowledge.

1.1.1 On being cognitive

Before going further it will be beneficial to clarify a key concept of this work: what makes this work about 'cognition'? Cognitive science is generally thought of as the study of the mind and its internal processes. However, recent work across the fields argues that the body plays a central role in our thinking processes. Cognitive Scientist Margaret Wilson writes:

> "Traditionally, the various branches of cognitive science have viewed the mind as an abstract information processor, whose connections to the outside world were of little theoretical importance. Perceptual and motor systems, though reasonable objects of inquiry in their own right, were not considered relevant to understanding 'central' cognitive processes. Instead, they were thought to serve merely as peripheral input and output devices (pg. 625, 2002)

Theories of embodied and situated cognition however argue that, "human cognition, rather than being centralized, abstract, and sharply distinct from peripheral input and output modules, may instead have deep roots in sensorimotor processing" (Wilson, pg. 625, 2002). Furthermore, there is an important relationship between design cognition and design computation. Research in design computation should address what theories of cognition it is based upon—the traditional information processing view or the embodied view.

I believe design cognition researchers have a narrow view of what design computation is. Perhaps George Stiny's work in shape grammars stands apart as a unique perspective on how seeing is a kind of visual calculation, but what about embodied cognition and its relationship to computation? There is an intertwined relationship between the two. This dissertation tries to approach design from the cognition research side. How can this inform the design computation side? It is important to distinguish what I mean by cognitive from cognitivism. In this work I take an embodied perspective on cognition. Cognitivism is rooted in the idea that the mind operates like a digital computer performing manipulations on abstract symbols.

1.1.2 Thinking with a body

"Movement is life," writes contemporary philosopher Mark Johnson (2009, 19). "We are born into the world as screaming, squirming creatures, and through our movements we get 'in touch' with our world...A great deal of our perceptual knowledge comes from movement, both our bodily motions and our interactions with moving objects" (Ibid, 19). Embodied thinking can be distinguished from spatial or visual thinking precisely because it involves a moving body. Bodies have orientations: they have a front, back, sides, and a bottom and so forth. Bodies can move themselves and also move the objects around them. Again, consider how we learn to play with blocks. Changing one's point of view is central to understanding the world of material objects. Philosopher Alva Noë writes, "When you experience something as cubical, you experience it as something whose appearance would vary in precise ways as you move in relation to it, or as it moves in relation to you" (2004, 117).

Furthermore, bodies have their own systems for self-awareness, motion control and tactile perception – proprioception through the somatosensory system. Bodies have their own memories too, a muscle memory. Through practice and repetition physical tasks become easier and require less thought. But what happens to that thought and the room left over in its absence when the body takes over?

The coupling between bodily-based action and idea generation has been largely absent in the development of theories of design thinking. Instead, the focus has been on either problem solving or visualization. Designers are said to work towards solutions in an ill-structured problem space, satisfying requirements in an as needed basis. Herbert Simon called this satisficing and used an information processing model to explain design action (Simon, 1969). Schön framed design thinking as a kind of situated experiment in which designers reflect on their actions (1992). According to Schön, designers construct their world as they proceed in seeing some quality in their sketch, making a move on it, such as drawing a new sketch, then they see it anew. Goldschmidt framed design thinking in terms of 'seeing as' and 'seeing that' (2014). And furthermore, seeing itself is an action in and of itself: Stiny activated the design thinking process through generative rules for seeing and making shapes (2006). Nigel Cross said that design thinking was a unique kind of intelligence separate and distinct from scientific reasoning or other scholarly methods for knowledge acquisition (1982).

The difference between these theories of design activity and what this dissertation proposes is the importance of the role of the body in driving design thinking. Examples of physical design thinking can be found in design fields of all types. From product designers to graphic designers, and from industrial designers to architectural and engineering designers, each works with his hands in interactive and exploratory ways. Product, graphic, and industrial designers need to see and feel their ideas in physical form. Architects and engineers need to make scale models to see spaces and test formal ideas. Product engineering design theorists Kris Wood and Julie Linsey write, "One important aspect of embodiment is modeling, or the testing of new implementation ideas by physical construction—building it—or by analysis—numerically modeling it (2007).

1.1.3 Thinking with things

Recent theories of embodied cognition from cognitive science provide a useful foundation to relate bodily based know-how with design thinking. The interactive form of thinking has been called many names including: embodied, situated, and recently, distributed and extended cognition. When thinking with things, it is a matter of mind-object coupling says cognitive scientist David Kirsh:

> "Handling an object, for example, may be part of a thinking process, if we move it around in a way that lets us appreciate an idea from a new point of view. Model-based reasoning, literally. Moving the object and attending to what that movement reveals pushes us to a new mental state that might be hard to reach without outside help (pg 2, 2013).

In this work I apply embodied theories of cognition to design activity placing emphasis on the role of the body in action as a driver of design thinking. In the embodied cognition perspective, our thoughts are said to ground out in the body and reach out into the environment through which we ultimately make meaning of the world (Anderson, 2003). Physical design thinking as a theory of design thinking can fit within these perspectives and also add a unique contribution to the field of design studies.

This work builds design research methods proposed by Nigel Cross, Bryan Lawson, Chuck Eastman and others in the field of design studies including design thinking and design computation. Cross writes, "Asking 'can a machine design' is similar to asking 'can a machine think'" (pg. 58, 2007). This proved to be a useful research strategy. By framing processes of design activity in terms of computer processing models of thinking researchers were able to not only understand design processes in depth in terms of discrete units but also they could propose novel computational tools that could enhance a designer's way of thinking. For example, this is how many of the CAD tools designers use today came into being. In the 1970s design researcher Chuck Eastman framed design activity in computable terms of input, algorithmic processing, and output (1970). Essentially, the designer was framed as an information processor with a mind in between input (perception) and output (action) functions. In this current work I model the designer as a dynamic coupling between action and thought.

Where past methods focused on thinking as a symbolic mental process, this current work focuses on thinking as an active physical process. Recent developments in computing technology suggest that computers will increasingly be integrated into our environment including computers that move and interact with us via visual, motion and tactile sensors. These are the technologies through which this work frames design thinking. These are radically different constructs that shape how we interact with computers.

1.2 Research Inquiry

Armed with embodied theories of cognition and looking at design research from a new bodily-based perspective we can now question how computational tools might support physical design action. What if the computer was not a static object but one that moved with the designer? What kinds of actions and what kinds of thoughts would be possible then?

1.2.1 Design Exploration through Robotic Interaction

Numerous projects illustrate the potential for such interactive physical computing technologies. For example, Willis and his collaborators have developed CNC fabrication tools that allow real time feedback between gesture and milling. Zoran and Paridisio created a handheld device that sculpts digital form through physical processes (2011). Other researchers have begun exploring how interactive manipulatives can enhance creativity. Kim and Maher (2008) and Maher et al (2014) study how objects embedded with computers change the dynamic of interaction. Braumann and Cokcan have developed gestural interfaces for controlling robotic arms using the motion of the body (2012). They explore physical computing technologies such as Arduino microcontrollers and Kinect cameras to develop programming platforms for novice designers to more intuitively and directly control robotic motion.

Such projects demonstrate how digitally integrated physical tools can engage the designer's body by means of haptic, motion, and infrared sensors. As robotics and other environmental computing technologies are subsumed into the design process, designers and design researchers will need theories of physical design thinking to frame the technical development in meaningful and productive ways.

By framing bodily based knowledge in terms of physical computation we can tap into it and expand it paving the way for interactive design robotics. My vision is for tools that open up new processes that extend design thinking. More than using robotics as fabrication and production tools, I envision robotic systems that become creative collaborators and teachers.

This work has implications for how the interaction between body, material and the environment can be enhanced with robotic partners. I imagine learning environments where students interact with robots to teach themselves independently extending their dexterity, coordination, and ultimately their thought processes. Later in this chapter we see that people think differently with one hand than they do with two. What happens when we have three or more hands with the aid of robotics? What new thoughts are possible then? We need to rethink how we learn with our bodies through physical interaction, how this impacts and extends the way we think, and how we can transfer this embodied knowledge to novice designers.

As collaborators robotic tools can not only double a designer's actions but also his thoughts. Being able to control another moving body will require a specialized kind of knowledge. Just how we learned to play with blocks in creative ways, we learned how to interact with others and in doing so we could work together to accomplish bigger goals. On a practical level, robotic manipulator arms can extend our reach and increase our speed, dexterity, and precision. More importantly, if equipped with vision sensors, they can see from new perspectives and see details we cannot, giving us insight into other points of view. Equipped with tactile sensors robots can feel and measure things we cannot. In material explorations they can test iterations and assist us in exploring multiple ideas. In model making activities robots can make duplicates, variations, and inversions and arrays. Imagine playing with blocks with a robotic partner. One could program pattern recognition algorithms to guide interaction between robot and designer. The possibilities are exciting. See the rendering in Figure 1.1 for an illustration of these concepts.

I believe robotic systems can demonstrate and test actionable techniques and principles. In physical design activity, understanding geometric spatial relationships is critical just as understanding principles of perspective is in drafting. I imagine special teaching materials that a robotic manipulator arm could transform and work with to demonstrate concepts that are difficult to learn through visual media. Concepts of repetition, massing, spatial relationships are critical in architectural design. Functions like movement, mass, and feel are critical in engineering and product design. Complex operations involving global variables could be taught as well. Our reach is limited by our two hands, but what if we had a third or fourth hand? Could we learn to think with extended and multiplied reach to act on systems of material?

Exploring these questions will not only benefit designers but also learners of all types of fields and industries. Manufacturing, assembly, and delivery services stand to benefit from interactive robotic technologies. We see this already emerging with robots like Baxter being used to augment humans in assembly processes. But more interestingly, design thinking is being integrated into many fields like business development, marketing, engineering, and computer science. How will design thinking change as we incorporate new interactive technologies in these processes?

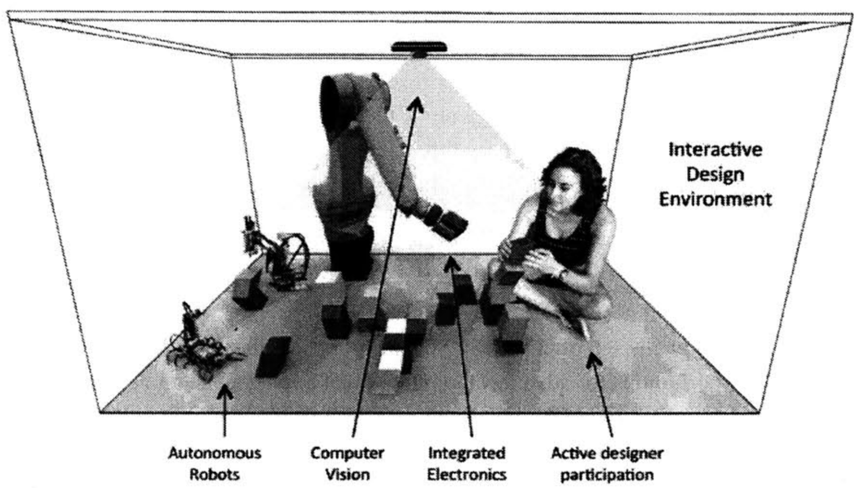


Figure 1.1 Interactive robotic partners can enhance creativity by challenging the boundaries of two handed manipulation. What happens when robots can increase our speed and dexterity? Robotic partners can also create computational relationships between material and body.

1.3 Impact: Enhancing Hands-On Learning

Ultimately I believe this dissertation will impact the potential for hands-on learning in creative design fields. The knowledge gained through embodied learning is difficult to transfer because it requires physical presence and often an apprentice-master relationship. This is costly and hard to scale up to larger groups of people. Robots can enable us to have extended bodily presence.

There are many barriers to overcome. First we must understand the nature of hands on learning. We need theory to explain the embodied ways we learn through physical interaction. How will learning environments need to be reshaped? Are some interactions more conducive for learning? Why are some people more adept than others? Can we codify expert interaction with computational principles? Embodied theories of cognition frame action as a kind of thinking that occurs outside the brain suggesting there are formal principles that structure interactive thinking similar to those that structure cognitive development. Second, we need to rethink what constitutes a teacher's body. Robotic technologies such as manipulator arms and environmental sensors can not only automate repetitive or difficult tasks but can also become interactive learning partners. We can embed the embodied know how of experts in robot systems to transfer their knowledge.

Lastly is the technical challenge of supporting exploratory learning in design. Working with robotics presents opportunities for advanced computational applications but the learning curve is steep. Robots are complex creations involving expertise from numerous fields. We need to make robotics accessible as well as fruitful to designers.

1.4 Research Project Overview: A Pick and Place Dream House

My objective with this work is to formalize the interaction between body and material in physical design activity in a way that can be embedded in robotic technologies and conversely, to embed robotic technologies into design behaviors. By studying how designers manipulate material to construct physical models we can develop a language of physical design thinking. Where does one begin? Model making is a highly complex activity involving many different kinds of materials and possible interactions. To reduce the complexity of this problem in my study I create a simplified design world – *a blocks world* – where model making as a design activity is abstracted to robotic terms of picking, transforming, and placing blocks in a configuration on a particular site.

In this simplified design world I can observe the actions of designers as they proceed along in the creative, open-ended task of designing one's dream house (Figure 1.2, top). Furthermore, by comparing different designers of various levels of experience I can make notes on the benefits of different interactions. To formalize the interaction I devise a coding scheme that structures behavior over time in terms of working with blocks to make configurations (Figure 1.2, bottom). My coding scheme is based on four primitive interactions: adding, subtracting, modifying, and relocating material. This coding scheme provides a way to discretely count specific types of interactions. By video recording the design sessions of designers and non-designers we can compare their interactions and body movements and using the voice out loud protocol analysis method relate these to what is said during the activity. Assuming designers do behave differently than non-designers, our central question becomes: what framework will best reveal these differences and explain them?

1.4.1 Why play with blocks?

Although block play is not necessarily a common activity in which designers engage, the idea of block play as a topic of research is not foreign in design studies research. Frank Lloyd Wright developed 'building gifts' from Froebel blocks as a set of formal rules in which to make constructions. Different patterns of arrangement could be formalized in terms of geometric principles, such as adjacencies, reflections, and arrays. Shape grammarist George Stiny developed his Kindergarten grammars proposing a constructivist approach to design generation based on the spatial relationships between Froebel blocks (Figure 1.3) (Stiny, 1980). He developed generative rules to replace the dependence on intuition or on a master designer to give guidance.

Design thinking pioneer Bryan Lawson also conducted studies on how designers play with blocks (1979). He compared how architects and scientists approached physical problem solving tasks when working with physical material. He found that architects more often worked towards developing a solution where the scientists worked towards refining the problem (Ibid).

In addition, block play is also a creative activity in which many different research participants could engage in. For more experienced designers it allows the opportunity to explore spatial relationships, volume, massing, repetition, and site constraints. For novices it allows easy engagement in a design activity that doesn't require extensive skills or background knowledge. The ability to engage many different backgrounds is critical.

Lastly, playing with blocks is a simple task that can be more easily duplicated with robotic manipulators. As part of the intention of this work is to envision how robots may enhance design knowledge, the ability to speculate in an informed manner is necessary. By using simple manipulation tasks we can set up comparison between human strategies and robot programming strategies.

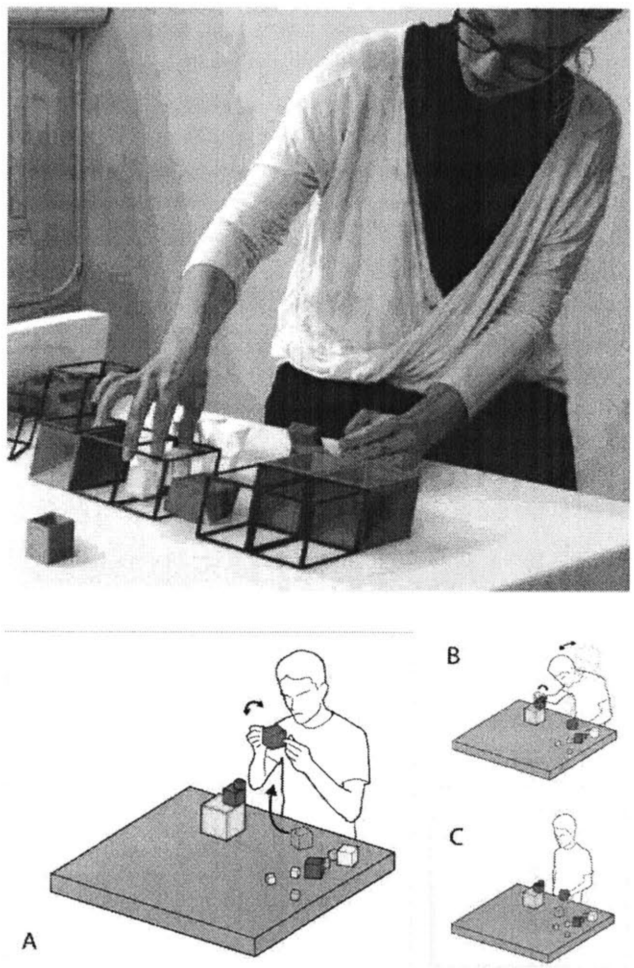


Figure 1.2 The experiment studied in this work involved participants arranging blocks into a dream house, top; many different coding schemes were tested to analyze the participant's interactions, bottom.

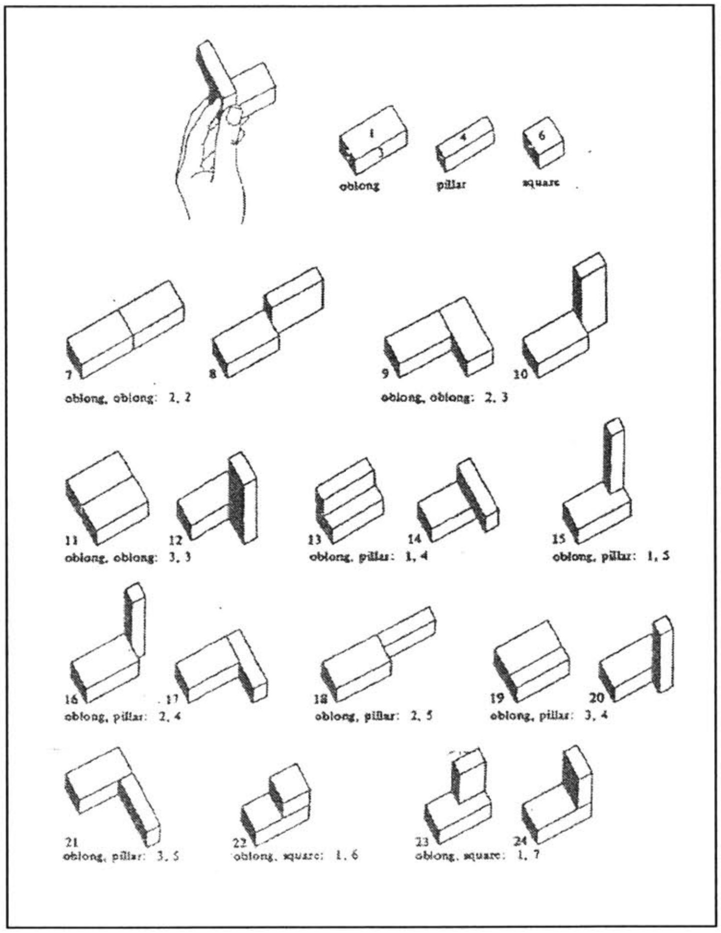


Figure 1.3 Stiny's Kindergarten Grammars exploit the physical and spatial properties of Frank Lloyd Wright's Frobel building blocks (Stiny, 1980).

1.5 Motivation of the Thesis

Many of the digital tools designers use today deemphasize or altogether remove the interactive nature of learning and exploration. From computer programming to 3D printers, the body's role is not engaged as part of the creative process. My motivation is to provide a theoretical and empirical foundation for the development of interactive design tools that enhance the bodily-based nature of exploratory model making activity. As digital technologies become more physical – more interactive and integrated into design materials and the designer's environment – theories of physical design thinking are needed to guide the development of meaningful interactive tools. Formalizing how designers interact with blocks may reveal insights into how physical design thinking may be enhanced.

1.6 Challenges in measuring physical design cognition

One of the challenges in this study is to measure design activity in terms that can be formalized and compared and ultimately enhanced through computational processes. Studies that measure cognitive actions in design activity have led to novel formalization of the design process and have expanded computational models of design knowledge. Design researchers Dorst and Dujkhuis (1995) identified two types of analysis: measuring the content of a designer's actions and measuring the process of actions over time. To measure and analyze design thinking, protocol analysis methods commonly represent the design process through coding schemes and segmentation. For example, Kavakli and Gero (2002) measure how the structure of design thinking in sketching activity differs between experts and novices. Suwa and Tversky (1997) use descriptive narratives of the design process made through video analysis. Additionally, accounting for the thoughts voiced by the designer in a design activity, a method known as the voice-out-loud or concurrent protocol method, have been used to understand design thinking (Lloyd et al, 1995). Some studies do account for the physical actions designers make, e.g., action such as sketching, looking, and gesturing (Suwa, Purcell and Gero, 1998). Such methods make it possible to analyze and compare how designers think and possibly, to extend a designer's creative potential.

1.6.1 Sketching as a visual way of designerly knowing

To a large degree much of what has been said of design thinking is about sketching activity. Protocol analysis studies have focused almost exclusively on sketching as the physical design activity. It is the means by which designers have 'reflective conversations' with their design (Schön, 1992); it situates designers and enables them to 'think on the fly' (Suwa, Purcell and Gero 1998); and it enhances a designer's ability to perceive visual-spatial features and conceive multiple design ideas (Bilda and Demirkan 2003). Indeed, much of design knowledge takes form as exploratory visual sketching activity.

1.6.2 Model making as a physical way of designerly knowing

However, sketching is not the only means of externalizing a design (Bilda, Gero and Purcell 2006) or exploring a design manually. Designers also make physical models, including: sketch models, diagram models, concept models, massing models, presentation models, and more (Mills 2011). Gürsoy and Özkar (2015) generalize two types of architectural models. Models *of* architecture serve to represent ideas that have already been resolved; models *for* architecture serve to explore and develop new ideas. In this work I am concerned with the latter. And unlike sketching, where design action is mediated on a plane, physical model making takes place in three dimensional space and involves interaction with materials in dynamic relationships. Physical models have many sides; what one sees depends on the configuration of parts in the model and also on his position in relation to the model. In addition, different modeling materials afford different actions: paper can be folded, chipboard can be layered, wood can be milled, concrete can be casted, and so forth. Such complexity gives way to entirely different design worlds:

> "Given a stock of available materials, different designers often select different objects, and even appreciate the 'same' objects in different ways, in terms of different meanings, features, elements, relationships and groupings, all of which enter into characteristically different design worlds" (Schön1992).

If sketching is thought to be a kind of *visual* design thinking (Goldschmidt 1994) model making can be considered a kind of *physical* design thinking. Yang (2005) calls 3-D prototyping a unique design language that embodies skill and time commitment beyond that of sketching. And yet while physical model making has been found to be beneficial to the design process in particular by giving students hands-on opportunities to test and refine design concepts (Lemons et al 2010) and by reducing fixation (Youmans 2011) very little has been said of model making activity as a kind of designerly knowing in action. As Schön said, "A designer's knowing in action involves sensory, bodily knowing" (1992 pg. 5).

But *how* exactly do designers think with their bodies and how can we make sense of this kind of action? There are many kinds of design activity that involve physical action, from tinkering, to making, to prototyping, and more. In my experiment with the dream house model, I explore how design concepts are formed with physical material.

1.7 Pilot Studies in Coding Physical Thinking

To illustrate the concepts introduced thus far I will present my methods for analyzing physical action in design activity. To develop these methods, I conducted a series of pilot studies in which I videotaped subjects as they completed simple interactive tasks manipulating and arranging different kinds of blocks. By re-watching the videos numerous times I could study their interactions, timing, and body movements and begin to compare how some designers performed compared to others. First of all, what counts as an action? Where does one end and the next begin? What is the best way to characterize the action as a way of designerly knowing?

The tasks given were closed-end, i.e., they had a correct solution. These included tasks to push and pull blocks into a pattern, pick and place blocks into a tower, and perform simple assembly operations to make a wall (Figure 1.4). I consider these to be fundamental interactions each involving basic motor skills. The tasks also constrained what kinds of interactions they were allowed to perform. Some tasks only allowed pushing and pulling blocks with one finger; other tasks allowed only the use of one hand. Other tasks involved two participants where one would give commands and the other obeyed. Further still, some tasks compared the mental vs physical interaction abilities of the participants. Together these close-ended tasks set a baseline for the final project in which I study more open-ended exploratory tasks—the dream house task.

1.7.1 Learning from humans to program robots

In parallel to these studies I developed robotic manipulator arm programs to complete similar tasks (Figure 1.4). For instance, the robot was programmed to push blocks on a surface with a poker and the robot was also programmed to pick and place blocks with a gripper. In these cases the robot was unaware of the environment within which it functioned. It was not capable of sensing or responding to unforeseen conditions, which the humans could do.

By completing the human and robot studies in parallel I could explore how the nature of interaction may exist in between or in combination of them. What are the differences in human behavior and robotic constraints? What can the human participants do better than the robot and what can the robot do better than the human? Can we embed knowledge from the human tasks into the robotic programs? Can we embed the knowledge gained from the robot tasks into human behavior? What might it look like for the human to work with the robot?

1.7.2 A push and pull task

The given task in this experiment was to arrange blocks from one pile into a certain configuration as seen in another pile (Figure 1.5). The participant was asked to complete the arrangement as quickly and efficiently as possible (in as few moves) using only his index finger. Surprisingly, in this highly constrained task I was able to identify 22 different ways of interacting with the blocks, e.g. underhand going toward the left, overhand towards to subject, or side hand going away, etc. Different subjects used different approaches to implement these techniques. Some only used one technique to complete the task while others used up to ten. It appears there are many different ways to use the body to solve a problem, but what accounts

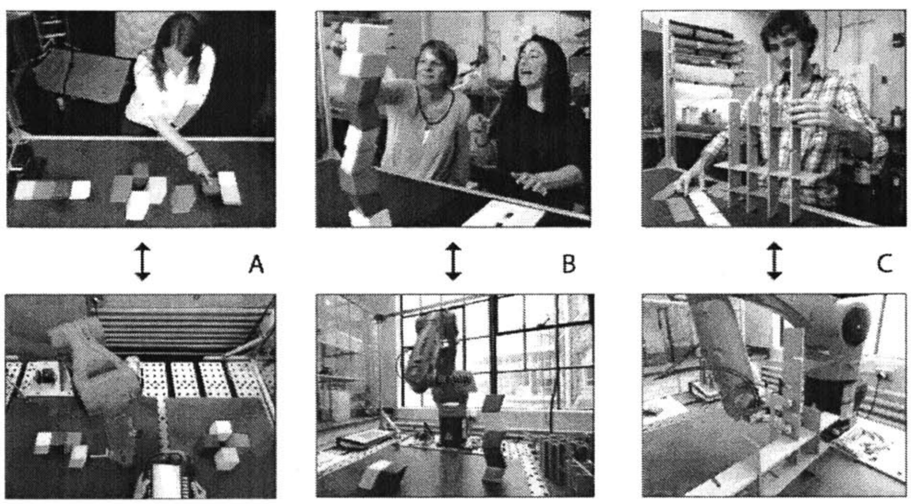


Figure 1.4 We can learn from human interaction to develop robotic manipulation programs. Understanding fundamental strategies in basic operations such as (A) pushing and pulling blocks on a 2D surface; (B) picking and place blocks in a 3D environment; and (C) simple assembly of interlocking components will assist us.

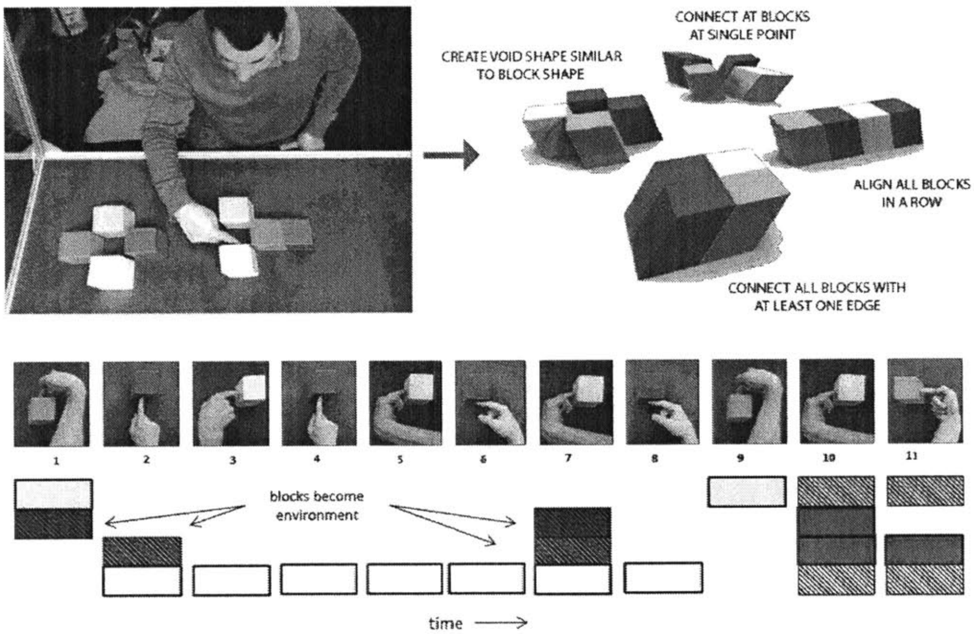


Figure 1.5 Push and pull task to arrange blocks on a flat surface. The participant repositions the blocks on the right to look like the blocks on the left (top left); interactions with the blocks can be analyzed in terms of the various positions of the hand over time to move the blocks (bottom).

for these differences? Do different actions lead to different thoughts which lead to different ways of getting to the solution?

Figure 1.5 shows a a detailed analysis of one subject's interaction sequences who used eight different interaction techniques. To analyze his interactions I developed a simple framework to describe action in terms of moving bodies, movable objects, and the world in which interaction takes place.

These three components were observed to be dynamic—they would seem to swap between themselves throughout the task; objects becoming bodies and worlds becoming objects. More than simply moving the blocks into place with different techniques, the participant would use other blocks to support the movement of the blocks that he was moving. At some points he would push the blocks along the face of other blocks as a way to constrain the motion. Because of their distorted shape, finding the center of mass (the ideal location to push) on the blocks was perceptually challenging. In this sense, while not in direct use, blocks would help structure the work environment, they would become the world in one instance and return to being moveable objects the next. This was seen to be done intuitively and seemed to be discovered along the way through interaction with the blocks.

This is the kind of bodily based know-how that we can embed in programs for robotic interaction. The robot can be trained to see structures in the work environment that can enhance the completion of a task. Worlds on not static, they are dynamic. Objects are not only objects but they can also become the structure of the world. Below is a program I created for a robotic manipulator arm to push and pull blocks (Figure 1.6) into a similar configuration. In the program the robot arm pushes blocks at a contact point off-center of the block so that it would be able slide across the neighboring blocks to stabilize the action.

1.7.3 A simple assembly task

In this task participants were asked to build a wall as tall as they could using interlocking laser cut pieces (Figure 1.7). Half of the subjects were allowed to use two hands and the other half were only allowed to use one. Not only did the one-handed subjects have difficulty with the actual assembly, which was expected, they also seemed to think about the pieces differently. In the sessions where the participant could only use one hand, they did not consider positioning the pieces vertically, as did all of the two-handed participants. The one handed participants attempted to gain height by stacking the pieces horizontally like Lincoln logs instead of vertically like how one would position 2x4's. Why was this? The ability to work with two hands would seem to give access to a different range of thoughts. Action scaffolds thinking.

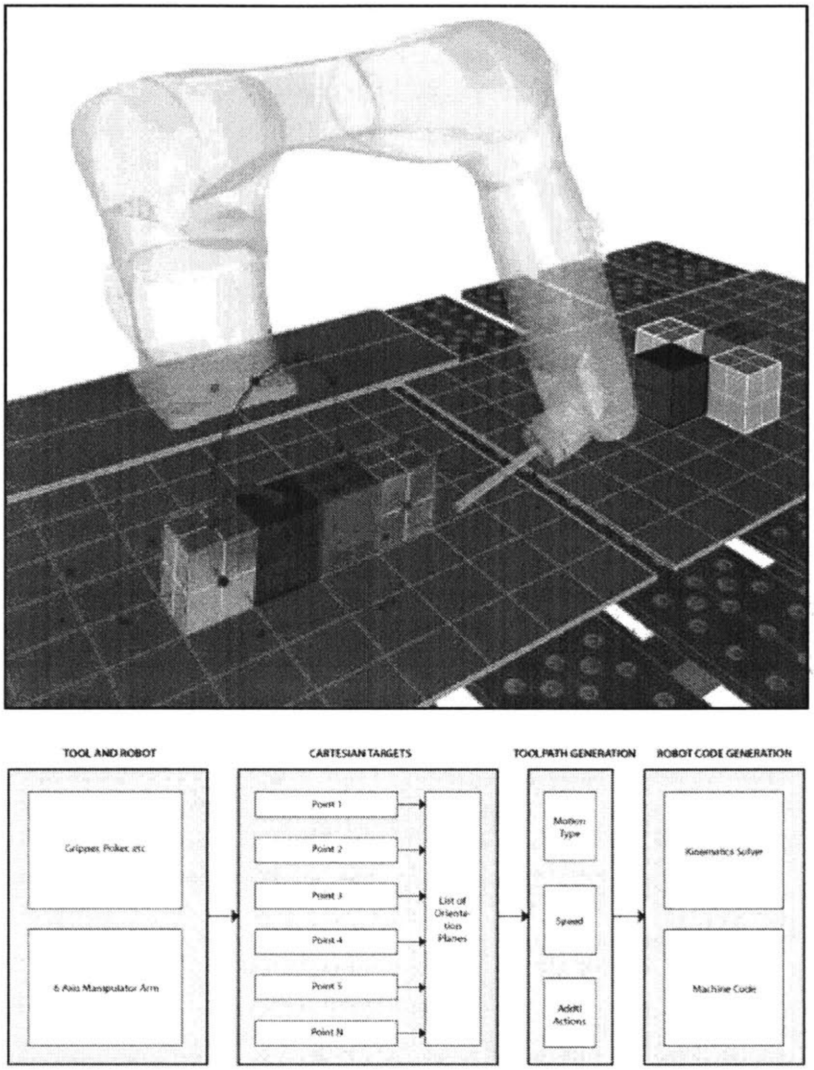


Figure 1.6 Robotic arm program scheme for pushing and pulling blocks.

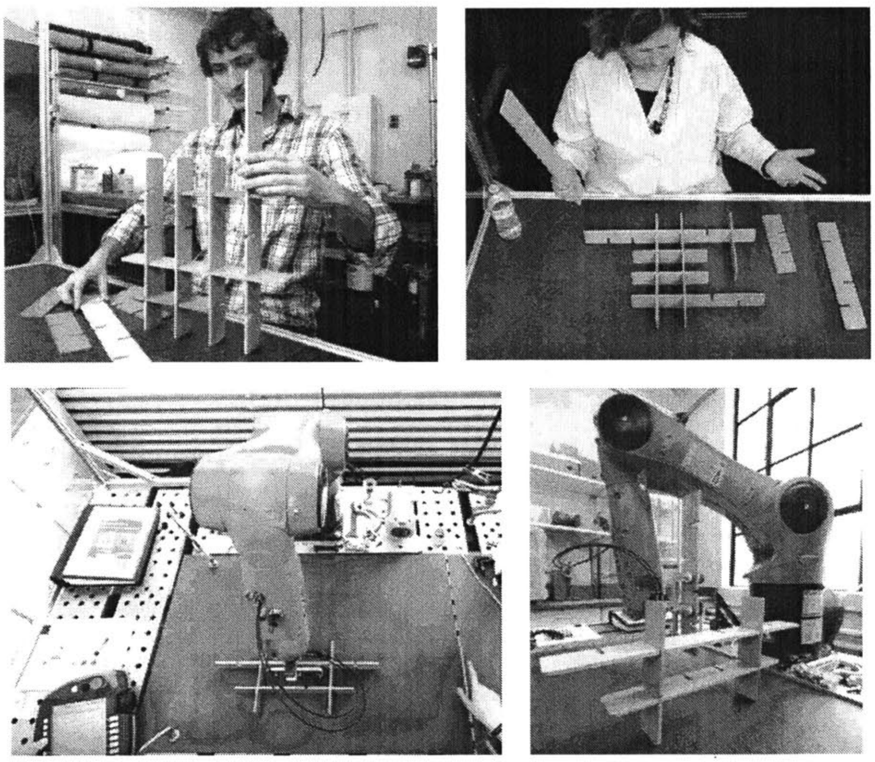


Figure 1.7 Differences were found in one vs. two-handed assembly tasks, top; using the table surface to stabilize on-handed robotic assembly, below.

With use of only one hand the participant's thought process was altered. After one of the one-handed participants finished he reported that he needed the table to stabilize the parts and therefore he never considered putting them in a vertical position. In two-handed assembly, one hand could hold the piece vertically and use the other hand to connect a new piece.

This kind of embodied know-how is useful knowledge for robotic-aided assembly. Similar to the push and pull task described above, I created a robotic program that could perform simple assembly tasks (Figure 1.7, bottom). Again, the robot was not programmed to sense its environment and acted in a predetermined fashion. Observing the human participants' action gave insight into how the robotic arm could be programmed. I found that with only one manipulator hand it was much easier to first assemble structures horizontally on the work surface and then rotate them up into vertical orientations.

Using the environment to stabilize the objects is an advantageous strategy. But we can go further in this line of thinking. What happens when humans and robots work together? What new thoughts are possible when humans can control additional hands? Our whole notion of collaboration can change.

1.7.4 Mental vs physical rotation

One last pilot study was conducted to explore differences between doing a task mentally and doing the same one physically (Figure 1.7). A mental rotation task of arranging blocks into a particular configuration is a common visual-spatial reasoning task. The ability to perform spatial operations in one's head is said to be a sign of visual intelligence which can be measured by the speed of completing the task. Our question is: how does this mental process compare if you are given a set of physical blocks to rotate? Is it easier to perform the task physically? Can you do faster if you work with your hands instead of mental rotation?

Unexpectedly, I found that participants took on average over 3.5X longer to complete the task with physical blocks (Figure 1.7). This is counterintuitive. I thought it be easier if the participants had more control of keeping track of configuration possibilities. Test one configuration with the blocks and check the solutions. Test another possibility and check again, and so forth. On the contrary, what I observed was that with the physical blocks subjects would often repeat the same mistakes; they would perform the same operations on the blocks without knowing it. Muscle memory is strong and can lead to fixation.

Additionally, we found that participants tried to complete the task fully with the blocks, whereas with the mental rotation task they would partially solve the problem and use process of elimination to finish it.

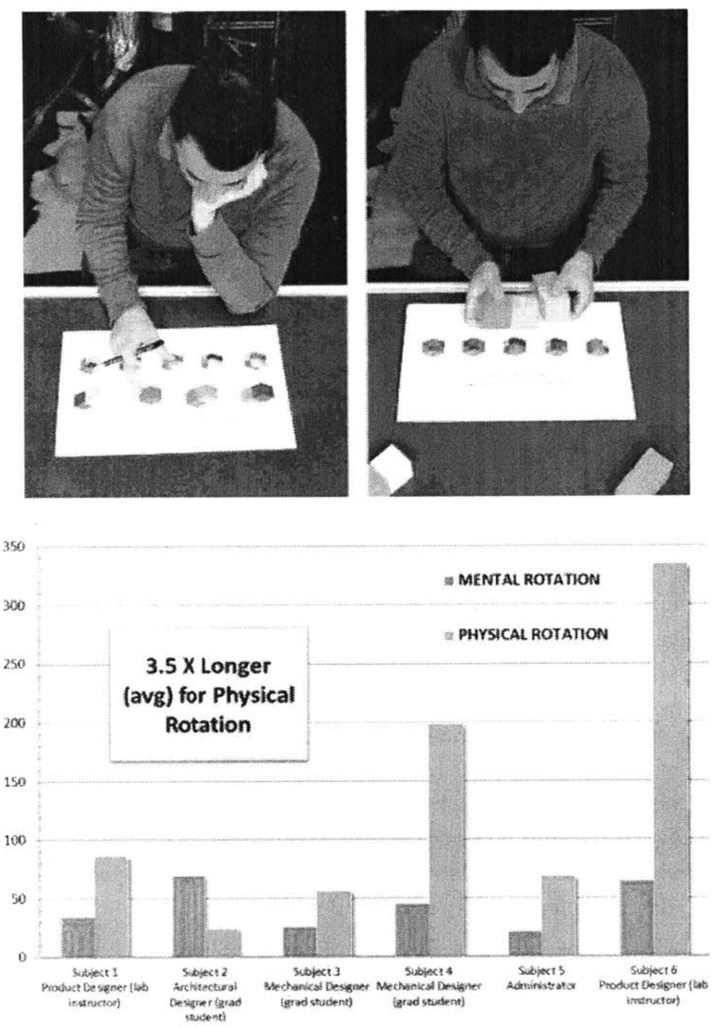


Figure 1.8 Tasks involving physical block rotation took much longer than tasks involving only mental rotation, top; the chart shows the results in terms of time to complete the task for six subjects.

These differences in mental and physical tasks suggest that we do indeed 'think with our bodies' in a way distinguishable from thinking with our minds. Our perceptions are altered, our goal-oriented strategies vary, and we each tend to employ unique physical manipulation techniques. The goal of this thesis is to first articulate in measure terms how this kind of thinking takes place in creative design activity. By studying the actions of designers we can develop physical computational tools in the form of robotic manipulator arms that may enhance such embodied know-how.

1.8 Dissertation Structure

These pilot studies reveal that there is something special about working with our hands. In closed ended tasks I observed many differences and strategies that could be formalized and embedded into robotic programming. However, the ultimate objective of the work is to examine creative, open-ended tasks. Can similar analytical methods be used when there is no correct solution in the task? How do physical interactions shape our creativity?

In the following chapters I lay out the work needed to explore this question. In Chapter 2, the background, I look at previous work in protocol analysis studies to shed light on useful research methods. This chapter draws from research I conducted in my general examination. As will be discussed, most of the work in this field has focused on sketching as the primary exploratory design activity. Common to protocol analysis studies is the use of coding schemes and segmentation methods. The challenge these studies present is to define the 'unit' of measure in design action. Many studies compare experts with novices to reveal designerly behaviors. Other studies look closely at the sequence of action taken by expert designers.

My focus on the other hand is on physical model making as an exploratory design activity. However, I believe a new theoretical framework is necessary to understand the embodied nature of model making. In Chapter 3 I present theories of embodied and situated cognition. These have roots in phenomenology and are commonly distinguished from symbolic information processing models of cognition. There are many illustrative examples ranging from gesture and dance training to early mathematics education. I look closely at the theory of epistemic action and compare it to Schön's concept in design activity of reflective action. I characterize the key difference between them as embodied action and embedded action. This contributes to the thesis question and proposes that designers may perform epistemic actions to inform their design thinking in physical terms.

Following the background section and theoretical framework, in Chapter 4 I present the research project proposal and outline my methods and central hypothesis. My claim is that in a physical design activity we should be able to observe differences in the behaviors of experienced architectural designers and non-designers. My framework encodes design activity in terms of robotic pick and place interactions: adding, subtracting, modifying, and relocating blocks. Project scope and limitations are addressed.

In Chapter 5 I present the results from the research project. Architects differed from students along three dimensions. First, architects were more controlled with the blocks; they used fewer blocks overall and fewer variations. Second, architects appear to think more about spatial relationships and material constraints. Lastly, architects more often experiment with block orientation within the model: position a block this way in relation to its neighbors and see what it looks like; reposition it another way and see what that looks like, and so forth. Together these findings suggest that designers interact with the material more effectively than students. They understand how to experiment physically with parts and the emerging structure.

In Chapter 6 I discuss the impact of my findings. I frame the discussion in the context of questioning how a robotic manipulator arm could serve as a interactive design partner. I present the simple but difficult challenge of programming a robotic arm equipped with a vision system to recognize and move shapes around on a flat surface. Further examples of interactive potential are presented as speculations. I show how a robotic arm could be used in three different ways: 1) as an action multiplier in which the robot can make arrays based on the designer's physical arrangement of parts; 2) as a bounded partner in which the robotic arm makes reflections of the designer's arrangements; and 3) as a rule detector in which the robotic arm sees shape rules that the designer sets and find other instances for copying the rule.

I conclude the dissertation in Chapter 7 with impacts, contributions, limitations and future work. There are three primary contributions of this work. First is theoretical: by bringing theories of embodied cognition, I open up the door for new ways of framing design activity in terms of physical action. The second contribution is the method I implement. I demonstrate with my coding scheme how we can frame design action in robotic terms of pick and place showing that experienced architects can be distinguished from novices and non-designers. The third contribution is a technical one which includes a program to enable designers to work interactively with a robotic manipulator arm.

CHAPTER 2

BACKGROUND

Design Studies and Analytical Methods

"When we think of designing...we are bound to attend to processes that computers are unable- at least presently unable - to reproduce: the perception of figures or gestalts, the appreciation of qualities, the recognition of unintended consequences of moves."

-Donald Schön

2.1 Introduction

Our world increasingly continues to be defined by digital processes that render knowledge to that which can be programmed on a computer. From smart phones to video chat and from laptops to cloud computing, digital technology is a highly ubiquitous aspect of our lives that frames the creation and transmission of knowledge. Design practitioners especially rely on technology to enhance their creativity, extend their communication, and expand their production methods. Visual-based digital design and fabrication tools have radically altered the processes for formal exploration in which designers can engage. But what is next?

The central question of the current work is: how can technology as a design tool be extended to enhance the designer's physical form of design thinking? As introduced in Chapter 1, the question has implications both on the methods of analysis and on the theoretical foundations of design studies. In this chapter I will address the analytical methods used in design studies.

To answer this, design researchers first need to ask the question of what design knowledge is – what does it mean to our generation? We need to ask this question in the context of current computational technologies: robots, environmental sensors, smart materials with integrated electronics. In what form does design knowledge exist in this context? Furthermore, how can we expand upon and improve it? Can physical design knowledge be embedded in our tools? Such questions lie at the intersection of research in design cognition and design computation, in other words—in how designers think about and do design in a formalized way. The methods through which design researchers formalize design knowledge frames not only how we see design as a creative activity, but also defines the future tools designers use and ultimately gives shape to the things they make.

The formation of the early theories of design knowledge framed the actions of a designer based on metaphors of the mind as a symbol processor, as was the common approach many psychologists of the day were applying to understand the mind at a more general level. Models of the mind were constructed as and tested with symbol processors—digital computers (e.g., see *Human Problem Solving* by Newell and Simon, 1972). Contemporary philosopher Hubert Dreyfus explains, "There is no doubt some temptation to suppose that since the brain is a physical thing and can be metaphorically described as 'processing information', there must be an information-processing level, a sort of flow chart of its operations in which its information-processing activity can be described" (pg. 164, 1992). For example, in *Human Problem Solving*, Newell and Simon apply the SIP framework to learning, organizational structure, concept formation and other domains like music, emotion, and design. "Symbols are patterns" (Vera and Simon 1993, pg. 9) and can be "of any kind: numerical, verbal, visual, or auditory (Simon 2001, pg 205). That symbols are largely verbalizeable statements such as propositions seems important however. Newell and Simon write: "A symbol structure designates an object if there exists information processes that admit the symbol structure as input and either (a) affect the object; or (b) produce, as output, symbol structures that depend on the object" (1972).

Applied to design activity, this symbolic computational framework suggested there are some external stimuli as input to the designer's mind; then there is an internal processing of the information in the mind; then finally there is an output in the form of an action in the environment. It was thought that if design knowledge could be encoded in such computable terms, then we could not only understand design as a fundamental human ability, but also compare and teach best practices in design, and furthermore, we could create technologies to ease the designer of cumbersome tasks, opening up room for new thoughts.

Other researchers presented contrasting views of design knowledge, however, and argued that symbolic based models limit our understanding of the tacit knowledge involved in design. Schön considered the symbolic approach as a key limitation of digital computation in design practice. He writes that "computers are unable- at least presently unable - to reproduce: the perception of figures or gestalts, the appreciation of qualities, the recognition of unintended consequences of moves" (pg. 156, 1992). Schön was saying that digital computation tools could not account for, support, or enhance a large part of what goes on in design activity largely because he saw design as a subjective conversation that designers have with materials and the situation. Designers construct their worlds in which problems could be solved as much as solve the actual problems. Such a reflective and dynamic activity could not be modeled in computational terms defined a priori. Schön writes, "Our ability to recognize qualities of a spatial configuration does not depend on our being able to give a symbolic description of the rules on the basis of which we recognize them" (Schön 1992, pg. 137).

My thesis proposes that design knowledge not only exists in the mind in the form of symbols but also in the body, in the form of actions. It is through our physical dealings with tools and materials and each-other that we interactively work through a design process. If we can understand this interactive process in computational terms we can enhance the embodied knowledge of designers. I draw from research on embodied cognition in cognitive science to help frame my questions of design knowledge in its physical form.

In the remaining sections of this chapter I review theories of design thinking including work by Nigel Cross, Bryan Lawson, Herbert Simon, and Donald Schön. From this foundation, I compare various methods for analyzing design activity. The earliest and perhaps most common method is protocol analysis, where the actions a designer makes during a design activity are recorded, segmented, and processed through visual and audio analysis. Another approach is Linkography pioneered by Gabriela Goldschmidt (Goldschmidt 2015). Here design activity is measured in terms of links between 'design moves'. Different patterns visualized in a linkograph determine the direction and number of links together which characterize the quality of a design process. I do not go into further depth with linkography. Another approach one could consider in design studies is the Situated Function-Behavior-Structure (FBS) approach by John Gero first described in its non-situated form in 1990.

Importantly, Gero's framework can be distinguished from the protocol analysis and linkography methods in that is doubly serves as a *prescriptive* model in addition to being a *descriptive* model of design. This thesis takes a similar approach in proposing that by more clearly understanding what goes on in design activity we can develop better suited tools for enhancing that activity. Gero and Kannengiesser suggest the potential for their framework to impact design tools. "This framework provides a new foundation for the development of intelligent agent-based design systems" and it "can make situated design agents potentially powerful enough to support human designers in the conceptual stages of designing (pg. 390, 2004).

2.2 Theories of Designerly Knowing

If there is to be a physical form of design cognition, then it should be relatable to current theories of design thinking. Understanding where these theories come has to do with the methods of study which are employed. Design theorist Nigel Cross identifies five such methods, including: Interviews, observations and case studies, experimental studies, AI simulation, and reflection and theorizing (Cross, 2011). This thesis employs many of these methods and draws from the rich history of design research.

2.2.1 Can a machine design?

Nigel Cross succinctly called the knowledge that designers possess a 'designerly way of knowing'. This implies that design knowledge is unique from other types such as scientific or scholarly kinds. Design knowledge can be distinguished through the kinds of problems that designers take on. Cross writes:

> "The designer is constrained to produce a practicable result within a specific time limit, whereas the scientist and scholar are both able, and often required, to suspend their judgements and decisions until more is known--'further research is needed' is always a justifiable conclusion for them" (1982, pg. 224).

Cross further suggests that design knowledge could be added to Howard Gardner's typology of human intelligence. Gardner's original categories of intelligence include: linguistic, logical-mathematical, musical, bodily-kinesthetic, spatial, interpersonal, and intrapersonal.

Cross was also one of the first design researchers to explore how design knowledge could be framed in computational terms as a research strategy. In his early work he said, "Asking can a machine think' is similar to asking, 'Can a machine design'" (2007, pg. 158). This became a productive metaphor because it allowed Cross to set up experiments in which designers interacted with a computer as an information processor that could help designers in real time perform calculations and recall needed information. Because of the limitations of computers in the 1970s and because no one yet knew how computers might best serve designers, Cross and his colleagues would replicate how computers could work by having a team of expert designers act as a the artificial intelligence of a computer. In one such experiment the design participants, separated from the expert designers, could write down questions via a computer terminal and the experts would quickly brainstorm and reply back with a solution. The objective of the experiment was to see what kinds of questions a designer might ask and in what way the computer could respond.

The implications of this experiment were that design knowledge, or at least part of it, could be captured and described in computable terms, and that the primary problem is the interface between the designer and computer.

2.2.2 What is design thinking?

Bryan Lawson identifies many types of thinking that humans engage in including that used in: remembering past events, paying attention to current events, belief systems, imagining future events, and reasoning through reflection and problem solving (Lawson 2005). Lawson claims that design thinking is perhaps some combination of them all, but primarily involve the last two types. He writes:

> ...reasoning and imagining were probably the most important to designers. Reasoning is considered purposive and directed towards a particular conclusion...When imagining, on the other hand, the individual is said to draw from his or her own experience, combing material in a relatively unstructured and perhaps aimless way" (2005, pg 137).

2.2.3 Symbolic foundations of design thinking

Simon considered design to be the act giving structure to an ill-defined solution space in a methodical problem-solving sort of way. In this view, the solution space of a design problem is fixed and design is thought of as a search process to find a solution within that space. The solutions designers pursue he noted are not singular however and so the designer proceeds in a way of 'satisficing' or coming up with heuristics for a 'good enough' solution as opposed to an optimal one (Simon, 1969). As Visser points out Simon's concept of satificing is useful for explaining the evaluation stage of design but not so much for the generative stage (2006).

To show how computers could be usefully integrated into academic design programs, a precise and explicit theory of design was needed (Simon, 1996). In proposing a curriculum for design as a science of the artificial, Simon lays out seven theoretical components:

1) *Theory of evaluation*: utility theory and statistical decision theory as a logical framework for rational choice between alternatives.

2) *Computational methods*: a) algorithms for choosing optimal alternatives such as linear programming, control theory, and dynamic programming; b) algorithms and heuristics for choosing satisfactory alternatives
3) *Formal logic of design*: adaption of standard logic to the search for satisfactory solutions.
4) *Heuristic search*: factorization and means-end analysis
5) *Resource allocation*: cost-benefit analysis of search process. Design activity is limited by time, money, people, etc. which need to be considered in developing the solution.
6) *Theory of structure and design organization:* problem decomposition and compartmentalization.
7) *Representation of design problems:* deciding which representation can make the solution obvious.

Simon held the view that design activity was present in many professions beyond that of traditionally conceived professions of engineering and architecture. He writes, "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (1996, pg 111).

2.2.4 A situated and constructivist approach

The symbolic information processing (SIP) approach is often contrasted with a situated approach to cognition (SIT). Particularly illuminating is a series of debate-like articles published in a special issue of *Cognitive Science* on situated activity theory, in which numerous authors were invited to write and then respond to each other's writing (Vera and Simon, 1993; Greeno and Moore, 1993; Agre, 1993, Suchman, 1993, and Clancey, 1993). Beginning with a seed article by Vera and Simon, the authors were given an opportunity to present cases for whether or not knowledge is fundamentally symbolic in nature (SIP) or it is contextually situated (SIT). Greeno and Moore sum up the central question underlying both sides:

> "The question, then, seems to be something like this: whether (1) to treat cognition that involves symbols as a special case of cognitive activity, with the assumption that situativity is fundamental in all cognitive activity, or (2) to treat situated activity as a special case of cognitive activity, with the assumption that symbolic processing is fundamental in all cognitive activity." (1993, pg. 20).

Vera and Simon take the SIP side arguing that perception, thinking, and action can be described definitively in terms of abstract symbols, or information:

> "Sequences of actions can be executed with constant interchange among (a) receipt of information about the current state of the environment (perception), (b) internal processing of information (thinking), and (c) response to the environment (motor activity)." (1993, pg. 19)

In Vera and Simon's theory a designer can be modeled as an input/output device with a mind in between that operates like the central processor of a digital computer. Based on this hypothesis, one of the key challenges has become an algorithmic based planning problem as a method for formalizing the cognitive steps involved in the 'internal processing of information'.

The situativity approach (SIT) on the other hand suggests a less dominant role for plans in determining action. In *Computation and the Human Experience,* Philip Agre takes a position on the seemingly contradictory nature of human activity as he notes it appears to be both improvised and yet routine (1997). It is only *seemingly* he argues because 'routine' is rooted in a 'planning view' of human cognition and action whereby "people conduct their activity by constructing and executing plans" in much the same way that a computer program would (pg. x). While people can and do make plans for guiding their future behavior admits Agre, he argues that plans, which together constitute a routine, which in turn forms the basis for action according to proponents of symbolic computing, are not responsible for any such future behavior. Hubert Dreyfus suggested this as well: "The important thing about skills is that, although science requires skilled performance be *described* according to rules, these rules need no way be involved in *producing* the performance" (1993, pg. 253, my emphasis). Agre proposes that human performance is a "continuous process of moment-to-moment improvisation...it is always a matter of deciding what to do *now"* (Agre p. x, emphasis by original author).

Visser outlines several shortcomings to Simon's approach of applying the SIP approach to design thinking. From overestimating the solution search process and routine problem decomposition, to underestimating the role of constructing problem spaces, a designer is rarely given a priori such clear boundaries within which to work.

As touched upon above, Schön is critical of the SIP approach to understanding design thinking because it requires a post rationalization that doesn't necessarily account for how thoughts proceeded in the moment. For Schön design activity is rather different than problem solving. It revolves around the conversation a designer has with materials and the context he is in. Constructing the problem to be solved is as much the problem as is solving it, perhaps even more so. Schön called this process problem setting characterizing it as 'move experiments' of seeing-moving-seeing (Schön, 1992). He writes that designers "need only recognize when something is mismatched to a given context and when a move makes that something better or worse in relation to its context" (1992, pg. 137-138).

Perhaps most important to Schön's theory of designerly thinking is his conception of the designer's ability to recognize *unintended* consequences of move experiments. This is reinforced by the notion that designers can do more than they can say. Actions are not always intended and so the ability to reflect on and recognize interesting unintended outcomes is central to design thinking. Shape grammarist George Stiny shares a similar viewpoint on how intention does not necessarily lead to recognizing valuable moves. He writes about how draftsmen proceed in design activity, "The draftsman always has the option to draw it in one way and see it in another—to forget what he's done, so that he can see and do more" (2006, pg. 134).

One of the limitations of Schön's work is his method of analysis. He constructs detailed vignettes or narratives of small scale design moves—sketching activity primarily. He draws from verbal protocols to build accounts for what the designer was thinking about. Although it provides a vivid picture of a designer's process Schön's method makes comparing design processes complex, if not impossible. The results are more anecdotal and less empirical.

Visser suggests that the SIP and SIT approaches to design thinking may ultimately complement each other:

> Studies conducted by reference to the SIP paradigm pay more attention to people's use of knowledge and representations in problem solving than to the construction of representations, and they do no analyze activities as they occur in interaction with other people and the broader environment. SIT-inspired authors focus on the consequences of people's interactions and the influence of the environment, the social and cultural setting, and the situations in which people find themselves, but they usually neglect the underlying cognitive structures and activities (2006, pg. 110).

2.3 Protocol Analysis Methods

As an analytical tool, design protocol studies have led to novel formalizations of the design process and have led to cognitive models of design activity (Dorst and Dijkuis, 1995). Design protocol analysis has been applied to many types of design activity including mechanical, architectural, graphical, software, and user interface design. Gero has extensively reviewed the many approaches to design analysis (Gero and Mcneill, 1998). Many studies identify their value through their ability to inform and advance tool making for aiding designers.

Protocol analysis methods have often been used to codify actions in design activity and correlate them with a designer's thoughts. Predominantly, sketching has been the activity that is analyzed (e.g., Suwa and Tvserky 1997; Suwa, Purcell and Gero 1998; Kavakli and Gero 2003; and Bilda and Demirkan 2006). Typically, audio/video recording is used to capture the design activity followed by retrospective or introspective reporting, where the participant is asked to watch himself in the video and verbally account for what he was thinking at the time. Another approach, known as the concurrent thinking aloud method, is to have the participant describe what he is thinking out loud while he is in the design session. The benefit of concurrent reporting is said to be a more accurate depiction of how thoughts unfold over time (Suwa et al 1998); whereas with retrospective reporting the account may be more thorough and also less disruptive of the design process (Suwa and Tversky 1997).

Common to protocol analysis methods is segmentation and coding schemes. Segmentation is the post-design session division of the verbal protocol into related 'dependency chunks'

(Suwa and Tversky 1997) that make up 'design moves' which reflect the designer's intentions. Segmenting is always subjective however and its reliability has recently been called into question (Perry and Krippendorf 2013).

2.3.1 Design as information processing

Protocol analysis methods have been in use since the early 1970s as a means for codifying design activity in terms of problem solving strategies. In one of the first protocol studies, Eastman (1970) analyzes the activity for designing a bathroom in terms of information states and discrete operations in which the designer engages. He formulated the design processes to consist of three stages: 1) Information types (inputs); 2) Operations on information types (processing); and 3) Information States (sequential flow of design process). His protocol was segmented into three types of information:

1) *Design Units* (the physical fixtures, e.g., toilet, sink, etc.)
2) *Constraints* (relationships between design units); and
3) *Manipulations* between Constraints and Design Units

The designer changes the information state by performing operations including: logical operations, corroboration, application, and inductive association (1970). The designer's verbal account for his own actions and reveal his intuitions established through drawing and sketching. Eastman found that, "Instead of generating abstract relationships and attributes, then deriving the appropriate object to be considered, the subjects always generated a design element and then determined its qualities" (1970, pg 33). Cross explains the finding saying, "This is a reflection of the fact that designers are solution-led, not problem-led; for designers, it is the evaluation of the solution that is important, not the analysis of the problem" (pg 4).

2.3.2 Design as an experience

A central problem of protocol studies is to define the unit of measurement. Dorst and Dijkhuis identify two paradigms for studying design activity which may inform a unit of measurement: (1) A positivist approach: studying design as a 'rational problem solving process' focusing on the process (e.g., Eastman, 1970), (Newell and Simon); and (2) a constructivist approach: studying design as 'reflection in action' focusing on the content (e.g., Schön, 1992). Dorst and Dijkhuis construct two parallel protocol studies to compare these two methods as a way to understand which one better captures the experience of the designer. They write, "The action is the unit for studying design" (pg. 274). In both studies they analyze the design (via sketching) of bicycle accessories. In the approach they code design activity along four dimensions:

1) *Acts*: sketching or thinking

2) *Goals*: establishing a concept, specifying a criteria
3) *Contexts*: whose perspective is considered? – client, users, etc.
4) *Topics*: specific attributes or components under investigation

Within each of these dimensions a unique identifier is given to specific types. For example, within the Acts dimension, sketching is labeled as '03'; within Goals, performance specification is labeled '02', and so forth. From this coding, graphs are generated revealing the sequence of actions in the designer's process (Figure 2.1).

Dorst and Dijkhuis identify many limitations of this approach and conclude that while the graphs may give a general sense of the design process and the variety of tasks involved, they are hard to read, do not convey the design concept, and importantly, they not signify the importance of individual categories (1995).

Dorst and Dijkhuis construct another protocol for the same design exercise however they record the subjective experience of the designer through the relationship of his design moves, problem framing, and the designer's 'underlying background theory'. Back tracking these three attributes along with the designer's verbal accounts, they establish a sort of script that reveals the design 'conversation' (Figure 2.1).

There are many benefits to this approach. Its primary benefit is the detailed account of how the designer perceives the problem. It preserves the process-content link over time. However, they conclude such an approach lacks structure and the process becomes hard to identify and therefore hard to compare with other design activities (1995).

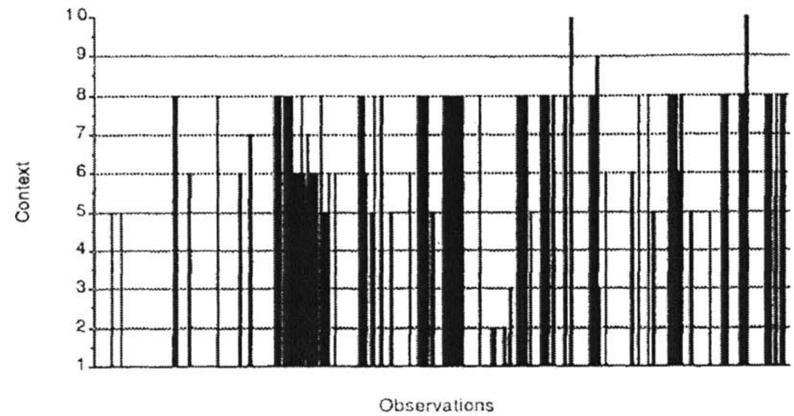
2.3.3 Cognitive interactions with sketches

Much attention has been given to understand the role of sketching in architectural design. Suwa and Tversky claim that experienced architects are able to 'read-off' nonvisual information from visual sketches and that by analyzing design activity in interlinked 'chunks' researchers may understand the cognitive nature of sketching (1996).

Detailed coding schemes are used to define and count actions within segments in the particular design activity. Many studies are based on Suwa and Tversky's original coding scheme (1997) which identified four information categories that architects see and think about while sketching: emergent properties, spatial relationships, functional relationships and background knowledge (Figure 2.2). In their protocol study Suwa and Tversky compared the relationship between these categories in the actions of experienced architects and novice students. The design activity that the subjects engaged in was to sketch a design for a museum over the course of 45 minutes. Each session was recorded with audio and video. Following the experiment the subjects were asked to watch the video of themselves and describe what they

Category 3: Context

None		00
Neutral		01
By stakeholders	- The company Hi Adventure	02
	- The company Batavus	03
	- The designer	05
	- The users	06
By aspects	- Ergonomical	07
	- Technical	08
	- Form	09
	- Business	10



005	there's no use starting from scratch if you can start at square two	BTH
006	stability's an issue	FR
007	doesn't directly take advantage of the frame	MV
	(efficiency in construction)	BTH
010	Centre of gravity is very high	FR
010	you want to keep that as low as possible	MV
012	don't try and reinvent the state of the art	BTH
014	stability (connected to Blackburn)	FR
019	don't redesign things	BTH
023	. . . wanted to know whats the trade of between carrying panniers on the front versus the rear	FR
025	Centre of gravity is very high (question to Blackburn)	FR
025	did it in the front (question to Blackburn)	MV
025	not much space between the frame (question to Blackburn)	MV
026	pack on one side (question to Blackburn)	MV
028	push it further back (question to Blackburn)	MV

Figure 2.1 The Contexts dimension considers who the designer is concerned with at different stages in the process, (Dorst and Dijkhuis, 1995)

And then I did the same thing *(i: drew a rectangle as a space for building).* Ok, building then is half of that *(i: the parking)*, but I thought, thin at the moment. I was thinking it might be long and narrow. So again I drew a long narrow one which was about 40,000 sq. feet at that time. *[action: drew a rectangle]*

Now I'm starting to say, Ok, gosh, how much of the site I cover with that!! *[action: move the sheet of paper on which the rectangle was drawn against the sheet beneath on which the property line was drawn]*

Physical

D-action

ID	index	content	dependent-on
Dc	new	draw a rectangle	

L-action

ID	index	content
L_1	continual	the rectangle for the parking
L_2	revisited	the figure '40,000'
L_3	continual	the figure '80,000'

M-action

ID	index	content

Perceptual

ID	index	content	dependent-on
Pfn_1	new	long & narrow shape	Dc
Pfn_2	new	the size of the new rectangle	Dc
Prnp	new	half the size	Dc, L_1

Functional

ID	index	content	suggested-by
Fi	revisited	a building function	Dc
Fr	revisited	numerical info. (40,000)	L_2
Fc	continual	numerical info. (80,000)	L_3
Fnp	new	building is half the size	

Conceptual

E-action

ID	index	content

G-action

ID	index	content	triggered-by	trigger
G_1	new	"draw a building of this size"	Fr	
G_2	new	"look at the parking rectangle"	K_2, G_1	L_1
G_3	new	"revise it to half"	K_2, G_1	Dc, Pfn_2, Prnp

K-action

ID	index	content	triggered-by	applied-to	produce
K_1	new	knowledge for calculation		Fr, Fc	Fnp
K_2	new	"look at a referent, then revise"	Fnp	G_1	G_2, G_3

Figure 2.2 four types of actions involved in sketching activity: physical, perceptual, functional, and conceptual (Suwa and Tversky, 1997).

were thinking about. This is known as retrospective reporting. One result they found was that architects have more and longer dependencies ('chunks') between their actions suggesting that architects think more deeply about ideas and get more out of the sketching activity.

Building on Suwa and Tversky's scheme (1997) and expanding the idea that the 'designer's action is the unit for studying design', Suwa, Purcell, and Gero (1998) define four types of actions as a top-down flow of information corresponding to the flow from sensory input to perceptual processing, and finally to semantic processing in human cognition:

1) *Physical*: Drawing, Body movement (gesture), or Looking
2) *Perceptual*: attending to features, relationships, and comparisons
3) *Functional*: relating non-visual information with spatial features (e.g., circulation of people through rooms)
4) *Conceptual*: making value judgments, setting up goals

These categories correspond to the flow of cognitive processes involved in human cognition: physical to perceptual to functional to conceptual actions. Physical actions include drawing, looking, and gesturing. Perceptual actions involve attending to features, relationships, and making comparisons. Functional actions include relating non-visual information with spatial features e.g., circulation of people through rooms. Conceptual actions involve making value judgments based on domain knowledge and setting up goals. The first two action types can be identified from the video recording; the second two types are identified from the designer's verbal account.

By charting the relationship between the four different types of actions and comparing them to the designer's verbal account after the design session, Suwa et al explain the cognitive processes in sketching. The process flows generally as the following: Physical (L2, L3) → Functional (Fr, Fc) → Conceptual (G1,G2,G3) → Perceptual (Prnp,Pfn2) → Physical (Dc) (Figure 2.3).

Such a detailed framework allowed Suwa et al to more closely analyze the interconnections between categories in the design activity of a single architect (Figure 2.3). In their analysis they hoped to see how 'bottom-up' physical and perceptual actions led to functional and conceptual actions, in other words, how they cognitively interacted with their sketches.

To understand the relationship between specific action types Suwa et al conducted statistical analysis on the correlations between pairs of actions (Figure 2.3). In particular in examining the relationship between physical actions and perceptual actions they found that physical actions such as looking and drawing induced perceptual actions. They write, "the role of drawing is to leave ideas down on a sketch as visual tokens, so that they can be revisited later for inspection" (1998, pg 480).

Most importantly, in examining the flow of design actions Suwa et al (1998) found that physical actions, along with perceptual actions are drivers of design thinking in sketching activity just as much as background knowledge and predetermined goals. Where previous studies primarily focused on analyzing how designers used plans, goals and background knowledge as problem solving strategies, their study shed light on the fact that, "Knowledge, strategies, goals and plans do not always initiate or control design actions. Rather, perceptual and physical actions play central roles in many ways" (pg. 482). In other words they found that actions drive thinking forward just as much as thinking drives thinking forward. They conclude that the physical actions of sketching enable designers to 'think on the fly'. Suwa et al (2000) elaborate on this idea:

> "[O]ur architect invented design issues or requirements not just by the use of explicit knowledge, but also by constructing justifications or reasons for them on the fly during the process. The construction of those justifications or reasons was dynamic in the sense that the architect did so through unexpected discoveries of unintended visuo-spatial features of the developing solution-space, i.e. design sketches" (p. 563).

By codifying the content of a designer's actions researchers have not only been able to speculate on the flow and structure of design thinking but also to compare novice and expert behavior. The differences found suggest there are learned designerly behaviors. Kavakli and Gero (2002) found structural differences in the behaviors of experts and novices. First they observed that in terms of the overall number of actions during a sketching activity, an expert is more active and productive than a novice. Furthermore, they found that the expert's rate of action increased over time while the novice's decreased. To account for this higher performance they identified correlations between co-occurring or concurrent actions in the protocol. They found that the expert was three times more selective in how many actions they would deal with at once, suggesting a more controlled and efficient design process.

The authors admit ambiguity is a problem when interpreting the protocol and suggest that the 'think-out-loud' may provide clarity for segmentation. They conclude that where most process-oriented protocol studies focus on the goals, plans and knowledge (expert systems, e.g.) as the dominant driver of a designer's actions, their results show that perceptual and physical interactions drive the design process and that "sketches serve as the physical setting in design thoughts are constructed on the fly and in a situated way" (Suwa et al, 1998, pg. 482).

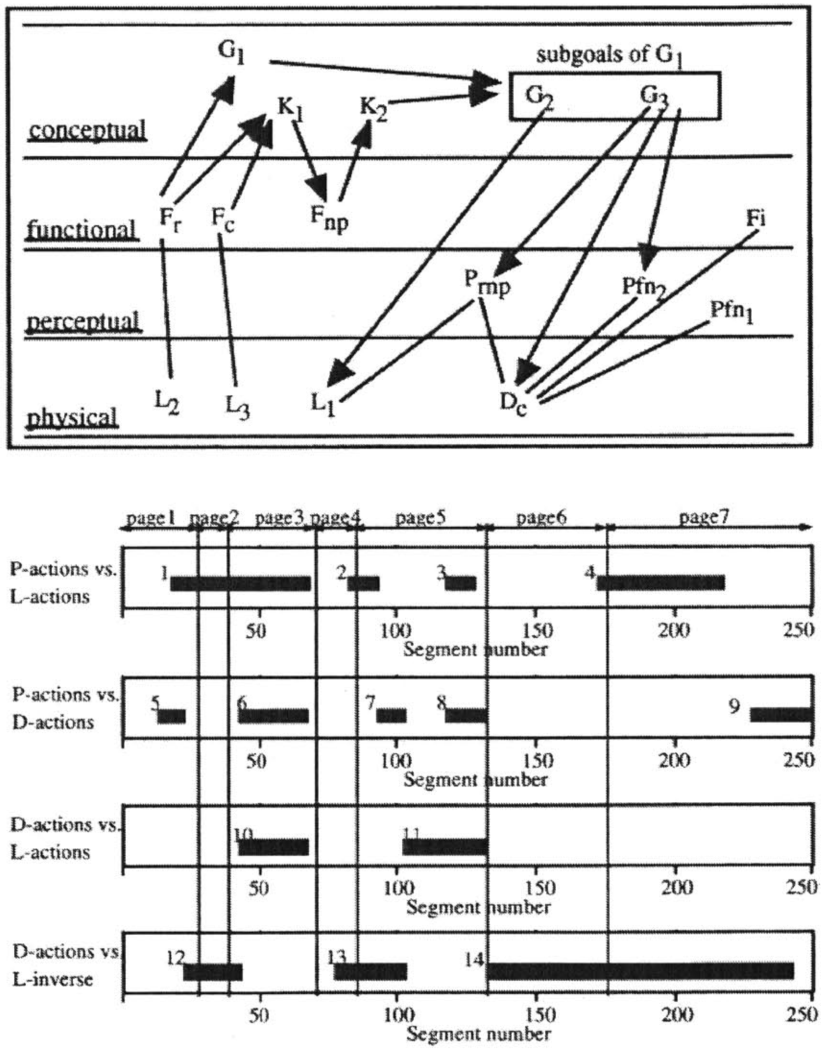


Figure 2.3 Relationships between designer's actions from Segment 1 of the protocol (Suwa et al, 1998).

2.4 Summary

The primary observation of these methods in design studies is that they break design activity down into a process with discrete units of measure. In my early work including papers and my general examination I was critical of these studies because I saw them as only extending the information processing approach to cognition. After further reflection however I see that these pioneering works really laid the foundation for understanding design more clearly. The challenging part of the work is to determine how you measure design. For sure, in any system of measurement you are by definition choosing one thing over another to look at and study.

2.4.1 Defining gaps in the literature

What is missing from the literature is an analysis of a broader scope of design activities. Why is it that sketching is the primary activity of analysis in design studies? This question is amplified in the technologies that are created to support design activity. Designers do sketch but they do so much more—they make models, they make prototypes, they test materials, and they run simulations.

In this study I look at model making as a primary creative development activity in design processes. In these early studies the focus was on sketching activity including the act sketching but also looking and gesture and perceptual activities as well. To further explore the physical activities we will need a different theoretical framework, one that emphasizes all the actions of the body. Next, in Chapter 3 I will present work from theories of embodied cognition.

CHAPTER 3

THEORIES OF EMBODIED COGNITION

A research framework

"We think; and as we think we feel our bodily selves as the seat of the thinking. If the thinking be our thinking, it must be suffused through all its parts with that peculiar warmth and intimacy that make it come as ours."

-William James

3.1 Introduction

In this chapter I lay out the theoretical framework that supports my thesis of a physical design cognition. I draw upon the theory of embodied cognition from cognitive science which argues that the body plays a more central role in shaping our thoughts. Contemporary philosopher Mark Johnson succinctly writes, "meaning and thought emerge from our capacities for perception, object manipulation, and bodily movement" (2007, pg. 113). As such the body serves as more than an input/output device to the brain and it is through the body's actions in the world that we are capable of understanding it. Pioneers in developing the theory of embodied cognition, Francisco Varela, Evan Thompson, and Eleanor Rosch write, "cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities...and these capacities are themselves embedded in a more encompassing biological, psychological, and cultural context" (1993, pg 173).

I briefly examine phenomenology and pragmatism as the theory of embodied cognition's philosophical foundations. Closely related to embodied cognition are theories of situated and extended cognition. Together these theories represent a counter perspective to human cognition from that of symbolic information processing models. Of primary distinction is the active role of the body, in terms of its ability to both sense its environment and also act within it. Additionally, the role of the environment as a driving factor in the cognition process is emphasized.

3.1.1 Research statement

I will use these theories of embodied cognition to help develop my research statement: that designers have a bodily-based kind of knowledge that they knowingly or unknowingly call upon to support their design creation process. It is through body-material interaction that new design ideas can be visualized and formalized. Embodied cognition paves the way to understand how this kind of action-based knowledge takes shape as a cognitive process.

I close this chapter with a discussion of two theories of embodied action, one from cognitive science, epistemic action, and the other from design studies research, reflective action. Linking these theories is one of the contributions of this dissertation.

3.2 Foundations in Phenomenology and Pragmatism

Embodied cognition draws from the phenomenological philosophies of Husserl, Merleau-Ponty, and Heidegger and the pragmatist philosophies of Pierce, Dewey and James. Husserl is said to be the father of phenomenology. His primary contribution was the recognition of the importance of the qualitative nature of lived experience. Husserl distinguished the Cartesian concept of an objective body from the subjective 'lived in' notion of the body (Gallagher, 2009). This was a departure from enlightenment thinking in which philosophical analysis was concerned largely with explaining the nature of abstract reasoning as a higher level of human thinking separate from our daily existence. Johnson notes that, "Phenomenology sought to remedy this grave defect by taking as its chief task the articulation of the character of so-called lived experience" (2007, pg. 70). Both Merleau-Ponty and Heidegger were influenced by Husserl's phenomenology. Merleau-Ponty focused his work on the bodily based nature of perception, while Heidegger focused on the situated experience in which we live.

Johnson writes that pragmatists in fact already had an embodied cognition perspective. "They argue that all of our traditional metaphysical and epistemological dualisms (e.g., mind/body, inner/outer, subject/object, concept/percept, reason/emotion, knowledge/imagination and theory/practice) do not mark irreducible ontological distinctions but are merely abstractions from the continuous interactive (enactive) process that is experience" (2007, pg. 153). Both phenomenology and pragmatism sought to explore the roots these abstractions. This chapter will not go into the details of each of these philosophies, but instead will highlight some important ideas and contributions that set the stage for the current form of embodied cognition.

3.2.1 Philosophy in the context of design knowledge

One of the fruitful outcomes of philosophical work at the foundations of embodied cognition is the development of a constructivist approach which to understanding design knowledge. According to Schön design is first and foremost a situation in which designers construct meaning. This is a distinction from the dualist idea that the world is a pre-given set of features to be perceived and decoded, such as the metaphor of design as a search process within a solution space. Instead, "Constructivism is a theory of learning according to which people create knowledge from the interaction between their existing knowledge or beliefs and the new ideas or situations they encounter" (Clancey 2009, pg. 20). I will return to this constructivist theory at the end of this chapter in the discussion of epistemic and reflection actions but it is valuable to note now the relationship to theories of design cognition.

3.2.2 James' feeling-thinking

Mark Johnson writes, "As the pragmatists argued, experience was never ontologically bifurcated in the first place, even though we can always identify aspects of our unified experience and abstract them as if they were separate and distinct entities, structures, or processes. Experience comes whole and continuous" (2007, 145). What Johnson is describing is the idea that feeling and thought can be separated in terms of percepts and concepts, a notion that pragmatists like William James in the early 20th century were avidly opposed to.

Instead of seeing them as different in kind, perceptions and conceptions are "two aspects of a continuous flow of feeling-thinking" (Johnson, 2007, pg. 87). Quoting from Johnson, William James writes:

> The great difference between percepts and concepts is that percepts are continuous and concepts are discrete...Each concept means just what it singly means, and nothing else; and if the conceiver does not know whether he means this or means that, it shows that his concept is imperfectly formed. The perceptual flux as such, on the contrary, means nothings, and is but what is immediately is (James, 1911/79, pg 32) (Johonson, 88).

3.2.3 Heidegger's 'being-in-the-world'

For Heidegger, practical experience, at a very literal level, i.e. what we do, when we do, and how we do is more revealing of human cognition than that of creating separation between mind and body. Heidegger writes, "The kind of dealing which is closest to us is...not a bare perceptual cognition, but rather that kind of concern which manipulates things and puts them to use" (1968, pg 95). Contemporary philosopher Shaun Gallagher illustrates Heidegger's concept of being 'ready-to-hand':

> "If, for example, I walk into my office, my primary relation to this setting is not as a collection of objects – desk, chairs, bookcases, computer, and so on. I do not think about the office door – I open it. I do not contemplate my desk or chair, I sit...To use Gibson's term, the affordances offered by the door, desk, chair, computer and so on, are implicit in the way that I interact with them – they are ready-to-hand" (2009, pg. 39).

Winograd and Flores further summarize Hiedegger's viewpoint that the existence of an external reality is best thought of as the act of interpretation of an event in which we are inescapably 'thrown'. It is not possible for us to have a neutral viewpoint since we are always immersed in our own interpretation. They liken this immersion to the experience of chairing a meeting in which:

1) *You cannot avoid acting* – you have a role of authority that must be upheld
2) *You cannot step back and reflect on your actions* – there's no time out, things are happening with or without you attempt to control the meeting
3) *You cannot predicate the effect of your actions* – there is no planning, you must 'go with the flow'
4) *There is no stable representation of the situation* – only after the fact does a clear picture of how the meeting went and objective analysis of patterns becomes possible
5) *Every representation is an interpretation* – however, even after the fact there is no one correct interpretation as everyone will see the event differently
6) *Language is action* – there are no neutral facts, speaking is itself the creation of a subjective viewpoint (1987, pg. 34-35).

3.2.4 Dewey's body-mind

Dewey's work places emphasis on the continuity between body and mind, and between organism and environment. This is a hard concept to understand, says Johnson, because it goes against our intuition and how learned as infants to make sense of the world. Johnson writes, "We learn to understand and to experience our world as consisting of pre-given, mind-independent objects that have discrete properties...we think that our world is given to us as a massive set of discrete perceptual inputs that we then have to put together or synthesize into the objects that populate our perceptual world" (2007, 73). This pivot is central to the embodied cognition theory of mind. "An embodied cognition view must avoid one of the most dangerous dualistic traps of Western philosophy," warns Johnson, "namely asking how something inside the 'mind' (i.e., ideas, thoughts, mathematical symbols) can represent the outside (i.e., the world)" (2007, pg 113). Dewey put it the other way around reversing this thinking. Instead, the world first comes to us as a singular and qualitatively pervasive whole from which we pick out features which we can then quantify. Dewey writes, "The underlying unity of qualitativeness regulates pertinence or relevancy and force of every distinction and relation; it guides selection and rejection and the manner of utilization of all explicit terms" (1934, 248).

3.2.5 Merleau-Ponty's body is not an object

According to Merleau-Ponty the body represents the possibility of movement and action through time. "My body appears to me as an attitude 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" (Merleau-Ponty, 1962 pg. 100). Gallagher further explains,

> "Merleau-Ponty means that there is no explicit or conceptual or reflective awareness of myself, or of my body, when I am engaged in my everyday projects. It is not, as if by some inner power, I conceive of a space through which I need to guide my hand as it reaches to grasp something; the shape of my grasp is not a representation of the object...The situation, then, is not laid out before me...I am in it and it is affecting me before I know it" (2009, 43-44).

3.3 Critiquing Cartesian Thoughts

Phenomenology grew from dissatisfaction with the Cartesian separation of mind and body. Underlying work in embodied cognition is the interactive nature of cognition which contrasts the view of the mind as separate from the body and the view of the world as existing independently and objectively from our lived experience. The thinking mind is what defined man according to Descartes and made him distinct from animals. Three central tenants define the Cartesian or 'cognitivist' approach: representation, formalism, and rule-based transformations. Internal states of thinking can be denoted with abstract symbols and "it is the *form* of the symbol (or the proposition of which the symbol is a part) and not its meaning that is the basis of its rule-based transformation" (Anderson 1993, pg. 3). It is the top-down accumulation of such representations and rules that define intelligence and therefore give way to the possibility for an artificial kind of intelligence. In the cognitivist perspectice, "The task of developmental and cognitive psychologist is to uncover [the language-like syntactic features and manipulation rules] and to understand how it is that they eventually give rise to the diversity that we appear to see in everyday cognitive activity" (Wilson and Clark, 2009, pg. 56).

Below are accounts of the cognitivist perspective on representation, formalism and rule-based transformation. The latter two can be coupled together in terms of physical symbol systems.

3.3.1 Physical Symbol Systems

Physical symbol systems as a theory developed by computer scientists and psychologists interested in modeling the processes of the mind represent the most clear example of Descartes' separation of mind and body. Symbols are patterns and always denote something other than themselves, including other symbols or sensory stimuli or motor action. Vera and Simon write:

> "A physical symbol system interacts with its external environment in two ways: (1) It receives sensory stimuli from the environment that it converts into symbol structures in memory; and (2) it acts upon the environment in ways determined by symbol structures (motor symbols) that it produces. Its behavior can be influenced both by its current environment through its sensory inputs, and by previous environments through the information it has stored in memory from its experiences" (1993, pg 9).

Key to this symbol information process is the representational perspective which characterizes the mind as the computational process of creating and assigning internal symbols to the external events happening around the body. Such a framework necessitates that an external world environment be duplicated internally to the observer. This does not require that all action be planned in advance, however. New symbols can be created through interaction with the environment both by means of motor and sensory actions.

3.3.2 Representational Bottleneck

Many early research projects collected hundreds of thousands of facts about the world in order to define the environmental parameters. This proves problematic when constructing an artificial intelligence in a practical sense: the amount of information needed to act in the world becomes exceedingly large; in fact, it is an intractable problem, constituting a 'representational bottleneck'. What information is relevant to the task at hand? Anderson illustrates this simple problem of a robot trying to navigate its environment: "For a heavy robot moving across a room the location and dynamics of big, solid objects is likely relevant, but the speed and direction of the draft from the open window is not. Unless the task is to carry a stack of papers" (2003, pg. 7). Such a problem led roboticist Rodney Brooks to say that 'the world is its own best model', meaning that instead of internally constructing an internal representation of the world and then acting, more intelligent agents would rather use their senses and goal-oriented actions in the environment to constantly redefine the environment. Still, the problem of acquiring meaning in such a dynamic coupling between agent and environment is unsolved.

According the Winograd and Flores four assumptions taken for granted in the information processing model or 'rationalist' view of cognition can summarize the view of a dualistic nature of thinking and being:

1) "We are inhabitants of a 'real world' made up of objects bearing properties. Our actions take place in that world,
2) There are 'objective facts' about the world that do not depend on the interpretation of any person,
3) Perception is a process by which facts about the world are registered in our thoughts and feelings and,
4) Thoughts and intentions about action can somehow cause physical motion of our bodies" (1987, 30-31).

3.4 Thinking with a Body

Embodied cognition is often framed in contrast to the symbolic information processing approach as introduced in Chapter 2. Psychologist Michael Anderson claims that central to work in embodied cognition is the symbol-grounding problem. Anderson writes, "The notion that grounding is at the root of intelligence, and is the place to look for the elusive solution to the relevance problem—for grounding provides the all-important constraints on representation and inference with which the purely symbolic approach has such trouble—Brooks calls the 'symbol grounding hypothesis'" (2003, pg 12-13.) Anderson cautions not to disregard the use of representation via symbols and suggests that looking to body may provide a definition. Anderson writes that symbols "must ultimately ground out in [terms of] the agent's embodied experience and physical characteristics" (2003, pg. 29). In other words, while we can and do use symbols to represent and communicate knowledge, these symbols depend on our bodies and the physical environment for us to make sense of them.

In their handbook on situated cognition, cognitive scientists Philip Robbins and Murat Aydede explain this dependence on a body:

[The embodied] approach to the symbol-grounding problem makes it natural for us to attend to the role of the body...our sensory and motor capacities depend on more than just workings of the brain...they also depend on the workings of other parts of the body, such as the sensory organs, the musculoskeletal system...Without cooperation of the body, there can be no sensory inputs and no motor outputs...without sensing and acting to ground it, thought is empty (pg 4).

For example, if we are an agent experiencing the world, how do we identify what can be defined as a 'chair'? Does a chair need four legs, a horizontal seat, and a vertical back? Does a bench count? How about a stump in the woods? The Gibsonian ecological perspective is that a chair is defined by its affordance of sitting. Anderson points out however:

"Simply having stored the fact that a chair is for sitting is surely not sufficient ground for this latter capacity. The agent must know what sitting *is* and be able to systematically relate that knowledge to the perceived scene, and thereby see what things (even if non-standardly) afford sitting. In the normal course of things, such knowledge is gained by mastering the skill of sitting (not to mention the related skills of walking, standing up, and moving between sitting and standing), including refining one's perceptual judgments as to what objects invite or allow these behaviors; grounding 'chair', that is to say, involves a very specific set of physical skills and experiences (2003, pg 12).

But what exactly is a body then? Johnson warns not to "speak of 'the body' and 'the mind', for that would simply reinstate the mind/body dualism" which work in embodied cognition strives to rethink. Instead it is better to think of the mind and body as 'abstractable dimensions of an interactive process' (2007, pg 274).

How the body ultimately acquires meaning is through its subjective sensory-motor experience—its own unique movement in the world. Johnson defines movement as having qualities such as "explosive, halting, weak, or jerky" (2007, pg 21) that span across four dimensions: "tension, linearity, amplitude, and projection" (2007, pg 22):

1) *Tension* – our ability to exert different levels of force through the skeletal muscular system. We learn to anticipate needed levels of force for specific tasks, however, if we misjudge, (such as lifting an unexpectedly empty suitcase) our experience is harshly revealed.
2) *Linearity* – we can control and vary the motion path of our movements that may bring us closer or further away from objects in our environment.
3) *Amplitude* – our motion path can be qualitative described such as expansive or contracted in its range of occupying space.
4) *Projection* – we can move forcefully or gently; slow or fast.

Johnson writes, "Movement is life...A great deal of our perceptual knowledge comes from movement, both our bodily motions and our interactions with moving objects" (2007, pg 19). For example, Johnson elaborates on how one may sit down into a chair:

"Perform any simple movement, such as sitting down comfortably in a chair and then standing up. Next, vary the performance of this motion in every way you can imagine: do it first fast,

> then slowly; now with an explosive effort, next with carefully controlled, gradual exertion; first jerkily, then smoothly; with body held taut and stiff, or with flowing grace" (pg 22).

For Varela, Thompson, and Rosch, to be an embodied thinking agent means two things:

> First, that cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context" (1993, pg 172-173).

3.4.1 Coupled interaction

Such an embodied approach to cognition leads to a coupled interactive understanding of the world, whereby there is no pre-given world which a perceiver is receiving and needs to decode through perception, but rather the world is defined by the coupled act of perceiving and acting.

In one revealing experiment two groups of kittens were studied in which they were raised in the dark and given limited exposure to light (Held and Hein 1958). During the exposure to light one group was given freedom to move around while the other was constrained and not allowed movement. The result was that the non-moving group was not able to navigate a space without bumping into objects or falling off ledges because they did not associate their motor capacities with their visual stimuli.

Margaret Wilson points out the evolutionary development of cognition as further reason to adopt the embodied cognition perspective:

> "It is argued that we have evolved from creatures whose neural resources were devoted primarily to perceptual and motoric processing, and whose cognitive activity consisted largely of immediate, on-line interaction with the environment. Hence human cognition rather than being centralized, abstract, and sharply distinct from peripheral input and output modules may instead have deep roots in sensorimotor processing." (2002, 625).

3.4.2 Six views of embodied cognition

Wilson claims there are actually six interrelated strands that compose the research program of embodied cognition (2002). Importantly she defines the idea of 'online' and 'offline' cognition. The degree to which any one of these most defines human cognition can shed light on what embodied cognition actually contributes to cognitive science. These six strands of research and theory include:

1) *Cognition is situated* – we act in terms of task-specific inputs and outputs. However, forms of 'offline' cognition also exist, as pointed out in Kirsh's critique (below), such as in activities such as day-dreaming or planning ahead. In contrast to Brook's

evolutionary argument, the ability to think in abstract, non-situated ways may be a more important evolutionary phenomenon to study.

2) *Cognition is time pressured* – humans act in real-time, whereas symbolic models of cognition allowed accumulation of facts to happen externally to a time sensitive task. Again, this is known as the 'representational bottleneck' by which the internalists' computational model have difficulty building up appropriate world models in a timely manner.
3) *We off-load cognitive work to the environment* – in time sensitive tasks, where the 'representational bottle' may impact our ability to cope with a situation, we can either rely on previously developed representations or we can make use of the environment to make generating new representations easier. A primary example of this is Kirsh and Maglio's theory of epistemic action. Both long-term off-loading and short term off-loading can happen. "Rather than attempt to mentally store and manipulate all the relevant details about a situation, we physically store and manipulate those details out in the world, in the very situation itself" (Wilson, pg. 629).
4) *The environment is part of the cognitive system* – thinking is not limited to the mind or body alone, but extended out and is inclusive of the environment. Clark distinguished between 'brain-bound' and 'extended' cognition (2009, pg x). Wilson is highly critical of this view because of its loose definition of what constitutes an interacting system.
5) *Cognition is for action* – vision may do more than build internal representations of what the world is, but also representations of how to behave in the world.
6) *Offline cognition is body based* – Wilson suggests that we can imagine bodily movement to aid cognition. For example, one can count by physically tapping his fingers consecutively, but one can also imagine tapping them as simulation of the physical activity. This may relate to Kirsh's study of 'marking' found in dancer's practice routines whereby the construct partially formed physical rehearsals to imagine certain new dance moves (Kirsh 2011).

3.5 Critique of Embodied Cognition

One critique of embodied and situated cognition is that many activities are not situation-dependent. Cognitive scientist David Kirsh suggests the following activities require some form of internal representation outside of a specific situation either relying on logical reasoning or recall: working with other people requires prediction about their actions; taking precaution for future events; following instructions such as a recipe; problem solving activities; and creative activities that have no external stimuli (1991, 171).

Another critique is of the hardline anti-representation stance taken in much of embodied cognition research. The critique seems to surround confusion over what counts as representation in the first place. Many researchers in AI claim that embodied and situational dependent forms of knowledge are in fact representations. As touched upon in Chapter 2, Vera and Simon (1993) take broad stance on the inclusive nature of physical symbol systems with regards to representations: "That the symbols in question are both goal-dependent and situation-dependent does not change their status. They are genuine symbols in the traditional information-processing sense... 'The-bee-that-is-chasing-me' is a perfectly good symbol" (p. 37). Furthermore, claim Vera and Simon, the embodied and situated approaches to cognition take for granted that symbol systems are perfectly capable of revising the definition of the world. They argue that situated or embodied action can be represented with symbolic formalization:

> "On the contrary, information processing theories fundamentally and necessarily involve the architecture's relation to the environment. The symbolic approach does not focus narrowly on what is in the head without concern for the relation between the intelligent system and its surround" (1993, pg. 12)

Vera and Simon critique the adoption of Heidegger's 'readiness-to-hand' concept when talking about the embodiment of learning. They claim that symbolic approaches more accurately describe the process of how tools become transparent through repeated use:

> "When a blind man first begins to use a cane, when a person is first learning how to drive, or when a person first interacts with a particular software application, they have conscious and direct representations of the equipment they are working with. Once these learning tasks are mastered, the equipment "disappears." Proponents of [Situated Action] would argue that, at this point, the relevant aspects of the situation are no longer in the user's head but in the interaction with the situation. The user is no longer consciously solving a problem or planning: He or she is "simply" doing.
>
> This claim involves a sleight of hand, however. As the task has changed from learning to doing, the information to be processed has changed as well. Information-processing resources are refocused onto the performance of the actual task, which is now less a matter of conscious selective search than it was during the learning period, and more a matter of detection (usually without consciousness) of perceptual cues, and automatic (learned) response to these cues. Both of these processes are symbolic, using the (cue -- response) mechanisms usually called productions (1993, pg 18).

3.6 Embodied Theories of Learning

3.6.1 Gesture and abstract concepts

Recent research in the learning sciences is grounded in theories of embodied cognition with one area of focus on the connection between gesture and learning abstract concepts. For example, Goldin-Meadow and Beilock (2010) demonstrate how specific types of gestural actions and their sequencing enhance the ability to learn mathematical concepts such as multiplication and division.

Alibali and Nathan (2012) demonstrate that students learn more readily when instructions include verbal and gestural information. This is known as multimodal learning. Martin and Schwartz (2005) demonstrate how interaction with physical objects like Montessori Blocks help children to learn mathematical concepts that they were unable to learn through mental representation only.

However, they also found that overly-structured environments make it difficult to apply learned concepts in novel situations. Carlson et al (2007) reveal how the movement of hands is integral to learning simple arithmetic by externalizing mental representations by aligning the phases of bodily movements such as pointing or nodding. Broaders et al show in connection between gesturing and mathematical learning by having children express themselves with gestural actions along with verbal descriptions (2007).

3.6.2 Learning in Dance

New research is expanding the significance of kinesthetic intelligence in relation to our imaginative powers. In recent work, Kirsh studies the use of abstract bodily motions called 'marking' in professional dancer's practice routines (2011). When learning new choreographies, instead of practicing the steps and phrases 'full out', more successful dancers devise limited bodily actions to simulate the full maneuvers. What this suggests is that contrary to the traditionally defined role of the body as an output device of internal thought, the body serves as a physical extension of thought capable of generating structure upon which new shapes, orientations, and sequences of thought are possible.

Warburton et al (2013) discuss similar findings with dancers who perform marking techniques, however they find that overly exerting during rehearsal diminishes successful real-time "full out" performance. They call this the embodied-cognitive-load hypothesis that suggests embodied activity exerts its own cognitive load and speculate that these 'reduction systems' may be found in other physical activities (2013, pg 1733).

3.7 Comparing Epistemic and Reflective Actions

I now turn to a particular theory of embodied cognition and attempt to relate it to design studies research. To restate my research question, I am seeking theories that may help explain how the body plays an active role in design thinking. As we have seen, embodied cognition provides many theories on the coupling between action and cognition, but how does this impact design studies?

To relate embodied cognition to theories of design cognition, I compare and contrast Donald Schön's concept of reflective action with Kirsh and Maglio's concept of epistemic action. Their similarities suggest that certain activities in the design process can be characterized as being embodied in nature. Such a recognition may lead to new insights about what goes on in design activity, primarily revolving around the use of the body.

Both Schön and Kirsh propose a novel conception of exploratory action. I speculate that Schön (1992) and Kirsh and Maglio (1994) are describing similar phenomena from the perspective of two different albeit related fields: design studies and cognitive science. These fields are different in their goals, but related in their common concern with computation and AI. Design studies explore how computational tools can aid, enhance, and/or automate design activity. Cognitive science studies human behavior and tests hypotheses with computational tools. To explore these relationships in more detail and provide clear examples of reflective and epistemic action, I will discuss the design exercises and experiments conducted by Schön and Kirsh, respectively.

3.7.1 Reflective Actions

Schön describes the phenomenon of design activity as a "reflective conversation with materials of the situation" through which designers perform a series of actions characterized as 'seeing-moving-seeing' (1992, p. 5). He expands 'seeing' into more meaningful terms like 'recognition, detection, discovering, appreciation' and 'seeing that, seeing as, seeing is' (1992). For Schön, 'seeing' is the ability of a designer to make subjective judgments. This approach to design studies has been contrasted to Herbert Simon's rational problem solving design process (1969), e.g. design as search (Dorst and Dijkhuis, 1995).

In Schön's observational studies the subject, Petra, begins a design exercise by drawing six rectangles in response to a programmatic need. She then performs another 'move experiment' (the act of drawing) and transforms the six rectangles into the three cross-hatched 'L' shapes (Figure 3.1, top). Such a move gives Petra a new way to see the original rectangles—what Schön calls 'seeing-as'. Although the original problem set in the design brief was to design six separate classrooms, hence, the six original rectangles, through her own intuitive reasoning she redraws and then 'sees' the six rectangles as three adjacent 'L' shapes. Thus her action of drawing gave way to having new thoughts.

3.7.2 Epistemic Actions

Kirsh and Maglio (1994) describe a phenomenon found in video game playing which they call 'Epistemic Action' whereby Tetris players utilize "physical actions [to] make mental

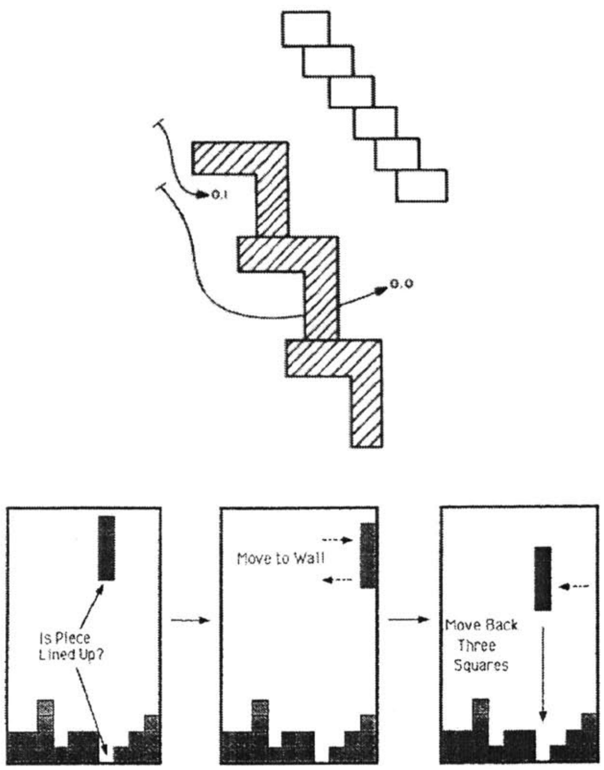


Figure 3.1 Seeing six rooms as 3 'L' shapes, top (Schön 1992); aligning Tetris shapes, bottom (Kirsh and Maglio 1994).

computation easier, faster, or more reliable" (p. 513) .They contrast epistemic action with pragmatic actions which are physical actions meant to execute pre-planned and goal-oriented steps. In their study, they found that players would perform seemingly extraneous physical actions during game play, such as overly rotating zoids or translating zoids across the entire screen, taking them further away from achieving the immediate goal at hand—dropping the zoids into rows. But ultimately, claim Kirsh and Maglio, such actions "make it easier for [Tetris players] to attend, recognize, generate and test candidates, and improve execution" [44].

In order to win the game of Tetris, Kirsh and Maglio's subject—let's call her, Tetra—needs to determine whether the vertical black shape (called a zoid) is aligned with the gap at the bottom as quickly as possible (Figure 3.1, bottom). Tetra also performs a sort of move experiment (pressing a button on the keyboard) translating the zoid across the screen and back again before she sends it to the bottom of the board. According to Kirsh and Maglio, this move relieves or 'offloads' the cognitive burden of having to mentally rotate the zoid in her head to determine its alignment. In doing so, the physical epistemic action gives Tetra a more 'full' and accurate perception of the zoid's alignment with the gap at the bottom.

3.7.3 Embodied and embedded

An important distinction between these two types of action is that epistemic action places importance on the physical movement as a temporal performance. In reflective action importance is placed on the remaining visual artifact—that is, the sketch in this case. In other words, it is a difference between embodiment and embedding. Embodiment couples the act of bodily motion with perception (i.e., judgment) in a dynamic process.

According to Johnson as discussed in section 3.4, as a bodily based performance, the quality in which Tetra hits the arrow key can be a smooth motion or choppy motion and this quality may affect her judgment. In fact, a more recent study has demonstrated a connection between motion quality and creative thinking (Slepian and Ambady, 2012).

Epistemic action is a kinesthetic and tactile intelligence that facilitates the exploration of creative solutions. On the other hand, with reflective actions Schön is concerned with how designers embed and see novel solutions within a visual medium such as a sketchpad. Others have also explored the concept of 'reading off' ideas from sketches when framed as a physical environment for discovery (Suwa and Tversky, 1997). Reflective action is a visual and spatial intelligence that facilitates the exploration of 'unintended' creative solutions.

3.7.4 Opposition to information processing models

Both Schön and Kirsh and Maglio contrast their observations with how information processing models might represent and execute their respective theories of action. Schön argues that proponents of information processing models (particularly researchers in A.I. who hold the planning view of cognition) make use of 'historical revisionism'—"reading back onto the beginning of a process what has emerged only at its end" (1992, p. 4). In other words, Schön is arguing that Petra is not an objective witness to the world; rather, she constructs her world through subjective and real time judgments. If Petra did execute an information processing model, she would have had to accept as a given the six rectangles as fixed primitives which she would combine in different ways. Kirsh would call such actions pragmatic actions. Instead, Petra performed a physical action to reshape the rectangles into three 'L's giving her a new insight into the problem and potential solutions.

Similarly, Kirsh and Maglio critique the information processing models (particularly the planning view of behavior found in A.I.) because it requires a pre-cognition to happen before any physical action can take place. The data from their Tetris experiments show that action in many cases precedes and facilitates cognition. According to the traditional model of cognition, before any physical action can take place information must sequentially pass through the vision and memory systems where an internal mapping between bitmap representation and potential trajectories are calculated, and then an action plan is executed by the motor system. However, this model does not account for their results which show superfluous actions such as overly-rotating zoids in expert player strategies (1994). The standard model of cognition and action only employs pragmatic actions. They write:

> ...[The standard model] reflects a bias that the type of environmental structuring relevant to problem solving, planning, and choice, as well as to recall and recognition, occurs primarily inside the agent. That is, the environmental structure that matters to cognition is the structure the agent represents (pg. 545).

Kirsh and Maglio's argument here is similar to Schön's argument against 'historical revisionism'. Exploratory activity whether framed as reflective action or epistemic action exploits and changes the world for the benefit of novel perception of the actor.

3.8 Summary: Impact of Embodied Cognition in Design Studies

Theories developed from work in embodied cognition may help structure the study of physical action in the context of design research. But what are the kinds of actions that designers perform? This question will be addressed in Chapters 4 and 5 to follow. The works of Schön and Kirsh and Maglio may shed light on the kinds of actions that matter in the first place, such as exploratory embodied and embedded actions.

The impact of embodied cognition is just beginning to be felt in design studies research. Although many have speculated about integrating the new theories of embodied cognition to reframe the design process (e.g. Gero and Kannengiesser 2004; Lyon 2005; and Visser 2009), little work has been done to empirically test the theories, let alone to implement formal computational systems. Most work simplifies the design task in order to formalize the embodied activities. Knight and Stiny (2015) for example develop a formalization of the physical actions involved in craft-making activities such as knot-tying. In their view, design, even in computationally aided processes, is not an intellectual activity but rather "a kind of making itself, an activity that demands perceptual, bodily engagements with the materials of the world (Knight and Stiny 2015, pg 26). Maher et al. present how physical interaction with programmable toys— Sifteo Cubes—leads to more creative solutions in simple word-play tasks. Using protocol analysis they investigate how gestures affect creative interaction by increasing the affordances of the programmed cubes (Maher et al, 2014).

3.8.1 Refining the research inquiry

With embodied cognition as a theoretical framework, specifically considering epistemic action, and with recent examples from design studies research which can be traced back to Donald Schön's notion of reflective action on how material and object interaction—as a form of 'move experiment'—impacts creative design thinking, there is opportunity to refine my research statement. Armed with the design research methods outlined in Chapter 2, in particular, design protocol analysis methods, my research inquiry can be restated as a specific question: What are the bodily-based epistemic actions that designers perform while interacting with material objects that may help them develop novel design ideas?

In the next chapter I describe the research project undertaken which explores this question in depth through experimental analysis and I outline the research methods and theories that support the motivation.

CHAPTER 4

RESEARCH PROJECT

An analytical study of designers in action

"When first you found some building blocks in early childhood, you probably spent weeks of learning what to do with them. If such toys now seem relatively dull, then you must ask yourself how you have changed."

-Marvin Minsky

4.1 Introduction

In this chapter I describe the research project undertaken. I outline the design task that was studied, the experiment participants, and the analysis method including the coding scheme, and the development of interaction categories. Together these terms help support my characterization of the design process as exploratory model making. The thesis statement, project hypothesis, research objectives, impact, and limitations are addressed, but first, I will pull together and summarize some of the important theoretical frames discussed in Chapter 3 in which we can re-purpose some of the analytical design research methods outlined in Chapter 2.

According to theories of embodied cognition, the body through its sensing, its movement and interactions in the world plays a primary role in how we experience the world. How we think is enabled through the qualitative and subjective nature of how we see and how we move. Contemporary philosopher Alva Noë calls the ability to make sense of the world our 'sensorimotor knowledge' because the very act of movement is linked to how we perceive (Noë 2004). In this view we do not need to distinguish between an internal world of the mind and external world of reality but rather we should see these together as an inseparable experience in terms of a process of interpretation.

This embodied and interactive view is a departure from the 'cognitivist', information processing view originally developed in cybernetic research programs in the 1950s. This view emphasized the symbolic representation and abstract logical manipulation of an internal mind as the fundamental characteristic of human experience. There are various extreme degrees of the views from both perspectives. For example, Andy Clark argues for redefining the mind as existing not alone in our brains or our bodies but also extending out to include the world as part of an incorporated thinking system (Clark 2011). Whether or not the embodied view or the symbol manipulation view is a more accurate depiction of our experience is not the central focus of this work. However, being aware of these differing perspectives and of their implications does matter because theories of embodied cognition have more than just philosophical implications.

What is important for the present work is to consider how an embodied cognition perspective alters the way we can frame the design process and ultimately determines what we may want to observe. In Chapter 2 I outlined key work in analytical design studies dating from the early 1970s to more recent studies in the late 1990s and early 2000s. As was found, a significant body of research in design studies was based on the conception of the mind as a symbol processor. According to Herbert Simon design was a search process, albeit dynamic, seeking potential solutions that were 'out there' in a predefined solution space, the world. In the analytical studies presented sketching is framed as an external environment in which the designer expresses thoughts and may also develop new thoughts. In design studies it is apparent that interaction with the environment and tools is critical in the design process.

Some studies do account for the physical and perceptual actions of designers in the design activity, such as their gestures, their gazes, their sketching. Donald Schön took a constructivist perspective in which design was characterized largely as the process of setting a problem and not necessarily in finding its solution. Schön emphasized the visual and perceptual nature of design activity, particularly in sketching. Accordingly, a design process was characterized as an experiment of 'seeing-moving-seeing' (Schön 1994). Design was seen as the ability to perceive spatial features, appreciate qualities, and "recognize unintended consequences of the moves" (Schön pg. 156).

These were important and impactful insights in design research; however, this dissertation starts with a different premise. My departure begins by asking why sketching is the primary object of analysis in design protocol studies. Sketching is indeed a common activity in design. It is used to quickly convey spatial information, programmatic information, as well as diagrammatic and symbolic information. Understanding the process by which a designer works through these relationships in sketching is very valuable.

However, sketching is primarily a visual activity not a physical one. In terms of considering how one can use a body, sketching it is a very limited activity. It is physical only in the sense that one must hold a pen or pencil in his hand and move it across a flat surface such as paper. From an embodied cognition point of view, sketching is rather uninformative in what it can tell us about a designer's sensorimotor knowledge. Surely designers do more than sketch. To understand the bodily based aspects of design thinking we must examine a different kind of design activity altogether, one that incorporates bodily interaction.

4.1.1 Exploratory model making in architectural design

In addition to sketches, designers make physical things. They make models, prototypes, and mock-ups, material studies, and so forth. In this work I am concerned with model making. As highlighted in Chapter 1, architects can be said to make two kinds of models: those that serve to represent preconceived ideas and those that serve to generate and explore new ideas. In making exploratory models, designers do more than visualize form or function; they enact it with materials. This kind of model making is a dynamic process of material manipulation and bodily movement over time. Materials are brought together and taken apart. They are manipulated in various ways; they are folded, twisted, sliced, and poured. As designers interact with materials they feel them, they construct forms with them, and they do this always in relation to their moving body. A moving body provides changes in perspective, in scale, and in occlusion—what can be seen from one angle may be hidden in another. Exploratory model making is a highly complex body-material interaction process.

From an embodied cognition perspective we should be able to provide an account of exploratory model making as a cognitive process in a design activity. This is the starting point for my research and it raises many broad questions. How do an architect's interactions with materials influence their design process? What kinds of material interactions are possible in the first place? Are there generalizable principles of body-material interaction? Can we observe differences between different designers with different levels of expertise? Also, what kinds of bodily movements are possible? Are all bodily actions serving the same purpose? If design is thought of as a process of reflection in action, in what ways do designers reflect on their material objects? Do they move around materials, zoom in and zoom out, pick them up and rotate them? Are some interactions or movements more conducive to creative design thinking than others?

The answer to these questions will largely be determined by the kind of model making activity that is analyzed and what kinds of materials are involved. For example, if an architect is making a cast concrete model his actions will include those that pertain to making formwork: measuring and cutting sheet material; fixing together cut pieces to construct the formwork; mixing together casting materials such as rockite compound; pouring casting materials; and releasing the cured form. If, on the other hand, an architect is working with paper material to construct a small scale model his actions will be very different. He can fold paper, cut it, and glue it together to layer it. How are these kinds of material interactions related to each other?

4.1.2 Blocks world: A simplified design space

Such a variety of material interactions makes model making as a generalizable activity a highly complex one to study. And while it is apparent that different materials will afford different interactions, what is not apparent is how different designers will interact with the same materials in different ways. Furthermore, there are many different ways of executing the construction of similar models and one way may or may not be more designerly than another. This makes comparisons across different designers difficult.

To reduce problem space complexity and make such material interaction comparisons possible, I introduce a simplified design world in which model making is abstracted to the manipulation of blocks. Models can be formed by bringing together blocks in particular configurations. Blocks can be added or subtracted to these configurations. Blocks can be rotated and translated in space or on a surface. Even within this highly constrained world, many creative decisions remain which make block play exploratory in nature: how many blocks to use, which blocks to use, what arrangement of blocks to make, in what order to arrange the blocks, how much time to spend with each block, and so forth.

4.1.3 Benefits of blocks world

Such a simplified world turns a design task into a 'toy problem'. This presents many benefits but also some limitations to the impact of the study. I will first cover the benefits. I will present the limitations in a later section. In an analytical cognitive study such as this one it is important to be able to identify discrete actions that may make up behaviors. In a more complex modeling activity such as concrete casting the variety and order of actions become enormous and ultimately, too cumbersome for a study of this size. Being able to distinguish discrete actions such as adding or subtracting or rotating and translating blocks makes in-depth analysis and comparison possible in a small scale study.

Another benefit to such a toy problem is that it makes it possible to include many different types of participants in the study. Such a simplified model making activity, one that does not require any specialized skill, can be done by not only 'expert' designers and 'novice' designers, but also participants with no design background at all. Everyone can play with blocks. But are there designerly ways of doing so? This broadens the scope of the study making it possible to discuss the impact of design training and design experience.

Lastly, this simplified design world makes it possible to introduce novel technologies such as robotics into early stage design processes. Such a study makes it possible to consider how robotics might enhance exploratory model making activity. Because blocks are rigid objects that can only be rotated and translated – one cannot bend them, twist them, cut them or make new ones – this highly constrained design task is likened to a pick and place task that robotic manipulator arms are commonly programmed to do. However, unlike a typical robotic pick and place task, the solution state of any particular design in this study is not known in advance and for each participant the solution is unique. Such a result makes robotics an exciting application for a cognitive study. A further discussion of the implications of robotic aided design processes is presented in Chapter 6.

4.2 Thesis statement

I take an embodied cognitive perspective of design which suggests that design is a physical activity that can be understood as a bodily-based material interaction process over time. Central to this claim is the assumption that one can observe and measure design thinking as a physical phenomenon. Such thinking can be found in the body-material interactions in early stage design processes, such as in exploratory model making. Therefore, the core of this work is to support this assumption by developing an analytical coding system that can reveal and distinguish physical forms of designerly thinking from non-design thinking.

The interactions between the body and material in the world form a temporal scaffold for bodily based design thinking—*physical design cognition*—by providing momentary structured opportunities for coupling epistemic material manipulation with 3D spatial visualization. The epistemic nature of material manipulation is essential to physical design cognition. It is through exploiting interactive material qualities, those that do not directly support or solve a particular problem, in which design thinking emerges. 3D spatial visualization is made possible through body movement around and within materials. The scaffold for physical design cognition can be studied to inform the development of physical computing technologies such as robotics and environmental sensors that can aid an exploratory model making process.

4.3 Hypothesis

The hypothesis of this thesis is that given an early stage exploratory design task requiring physical material manipulation, I will observe differences in the kinds of interactions and body movements exhibited by experienced architects from those exhibited by novice students and non-designers. These differences can be characterized as epistemic actions vs pragmatic actions. Architects will more often perform actions on blocks that do not directly support the building of structures, but that help them see and test new forms more readily. On the other hand, non-designers will perform more interactions that directly support completing the design task. Furthermore, in the blocks world that is set up these epistemic differences can be described in terms of a pick and place robotic manipulator arm code: adding, subtracting, modifying, and relocating blocks on a site model.

4.4 Research Objectives

The first research objective is to develop an analytical framework that can capture a broad yet specific range of material interactions involved in an exploratory design task. This requires observation of the participants to determine what interactions are relevant to begin with. For example, should the framework be able to distinguish between when a subject picks up a block while looking at it vs picking it up while not looking at it? Or is it more important to identify the number of block rotations? What level of detail should the framework analyze? Does it matter if a subject picks up a block with his right hand, passes it to his left hand and then places it? What is the framework that best reveals physical design thinking? Exploring this question is the primary objective of my dissertation. A successful outcome will be a framework that can distinguish between different levels of design expertise.

The second research objective is to apply the framework to a given design task and to identify the different forms of epistemic designerly interactions. There is certainly more than one kind of epistemic action that can be observed design activity. In what ways do experienced designers and non-designers interact differently? In what ways do experienced designers differ from each other? A successful outcome of this objective will be in the characterization of designerly interaction in a model making task.

The third objective of the study is to explore how a robotic manipulator arm could enhance and automate certain forms of physical design thinking. Ultimately, this dissertation is about creative robotic interaction. In what ways can interactions with a robotic partner enhance physical design thinking? In what ways can a robotic partner help non-designers become more designlery? Developing an interactive robotic system presents many technical challenges but will help illustrate the potential impact of the thesis. A successful outcome of this objective will be a typology of human-robot interaction programs.

4.5 Impact

By considering the body-material interactions in early stage exploratory design activity as a kind of design thinking itself we can broaden the definition of what constitutes design knowledge. We can capture a new perspective which was largely considered as an intuition or a sort of tacit knowledge that was hinted at but never formalized. By formalizing this knowledge we can integrate new technologies into the early stage design process that may enhance and extend the designer's reach.

This will impact in the foundations of how designers think of themselves. They will be coupled with robotic partners in a design process. Thinking with two hands of your own in addition to robotic arms changes what we're capable of in a physical way. This is very different from the way we think of computers, as tools and not partners. What makes robots different is their embodiedness. As embodied being ourselves we will relate to other bodies differently than simply tools.

4.6 Limitations

The primary limitation of this study is that the medium of interaction—blocks—is not a typical material that designers work with. Designers do interact with physical, three dimensional materials, but they typically perform more complex operations on them such as cutting, folding, or gluing. By limiting the study to a 'toy problem' there is risk of making the results irrelevant to the needs of current design practice. However, I believe this study sets up a foundational groundwork by looking at very basic interaction types which can be applied to more advanced material interactions in the future.

Another limitation of this study is that it examines designers working in isolation. This is not typical in design practice. Designers often work in pairs and teams of people. Understanding how multiple designers work together through material interactions may provide even more data to inform how robotic partners could be integrated in the design process.

4.7 Experiment Set-up: A Dream House in Blocks World

The participants in this study were tasked with making a physical model of their dream house by arranging blocks on a wooden site model (Figure 4.1). The task was open-ended: no specific program such as the required number of rooms or square footage was given. Neither was a particular scale given; a single block could represent the entire house or a piece of furniture. They were provided 44 3D printed parallelepiped shaped blocks of which they could use as many or as few as needed. The parallelepiped shape enabled more complex assemblies with varied spatial relationships. The unique spatial properties of the parallelepiped shape are further addressed in the last section of this chapter. No other tools or medium (e.g., no pencil or paper) were allowed. Participants were given up to 15 minutes to complete the design task. They were encouraged to voice out loud any thoughts they had about their design or their process while they manipulated the blocks.

Video/audio was captured from above the site model and photographs were taken throughout each session. The participants were not told how the dream house would be evaluated other than that at the end of their time they should be able to walk the researcher through their model to describe what they were thinking.

4.7.1 Participants

The participants of the study were categorized into three groups: expert architectural designers, novice student designers, and non-design students. Three experts, three novice students, and three non-architecture students were selected for participation (See Table 4.1 below).

The expert group included 3 men with a mean age of 36. All experts were professionally trained practicing architects with 4-8 years of teaching experience at the college and graduate level. The novices were either sophomores or juniors all enrolled in the same architectural design department. All novices had taken at least one design studio prior to this experiment. The novice group included 3 women with a mean age of 20. The non-design students were all undergraduates enrolled at the same university as the novice architecture students; however they were from different departments including computer science, physics, and material science. This group included 1 women and 2 men with a mean age of 20.

Table 4.1: Study Participants

Experienced architects (experts)	3	3M, 0F
Students in architecture (novices)	3	1M, 2F
Students in non-design fields (non-designers)	3	2M, 1F
Total	9	6M, 3F

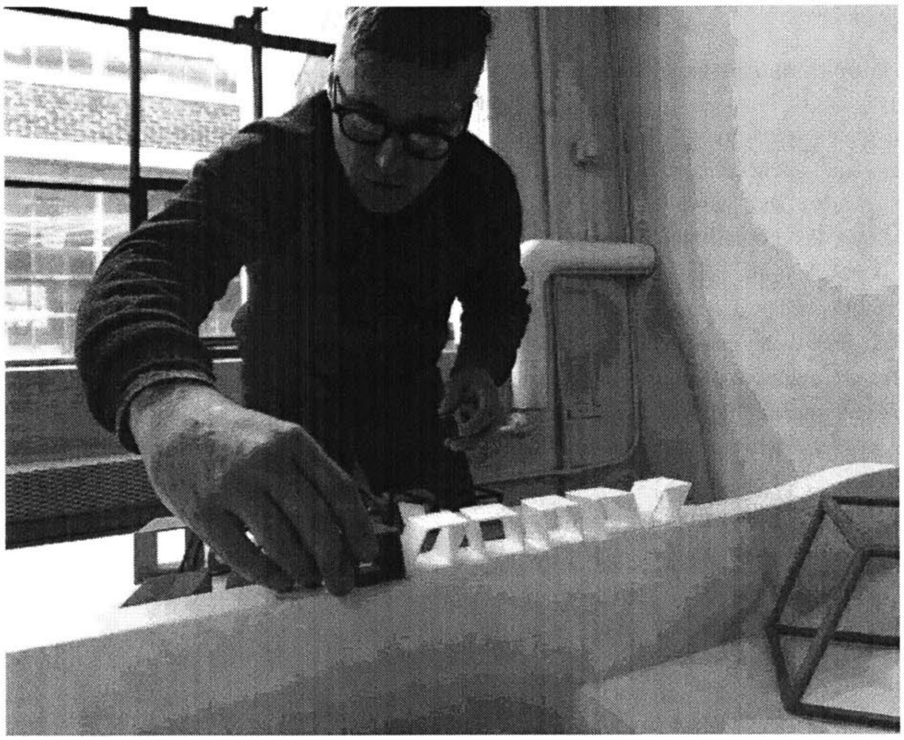


Figure 4.1 An architect placing a block in a configuration on the site model to test its fit at different angles.

4.7.2 Site model as environment for interaction

The participants were provided a 4'x4' (approximately) wooden surface on which they were to construct their dream house (Figure 4.2). The site model was intended to serve as a playground for creative block manipulation. The site model was designed with a variety of sloped and flat surfaces, textures, and elevation changes to offer different settings for the dream houses to be constructed. The model was fabricated with various wood working tools including a table saw, chop saw, circular saw, and a CNC router. It was laminated from many layers and then painted white and sanded smooth to provide a monolithic surface.

4.7.3 Blocks as material to interact with

The participants were given 44 3D printed parallelepiped shaped blocks with variations in size, color, and opened/closed faces (Table 4.2) (Figure 4.3). The parallelepiped shape is essentially a cube that has been sheered along two axes with the resultant shape being a distorted cube. Perceptually the parallelepiped shape looks like a cube from most viewpoints; however it behaves unexpectedly under rotations. The blocks were printed with a Stratasys Dimension 3D printer. There were three general block types: open face, wireframe, and solid. There were three different size blocks: ½ scale, 1/3 scale and ¼ scale (relative to each other). The blocks were simple enough to learn within a few minutes how to build structures. Yet, they were complex enough to make interesting and surprising forms which would be of concern, especially to the architectural designers. The motivation behind using the parallelepiped shape is described at the end of this chapter, section 4.10, in terms of its symmetries. If the blocks were typical cube shapes, there was risk that the more experienced architects might find the task too elementary.

4.8 Method

Video-based protocol analysis and concurrent voice out loud methods were used to codify the subjects' interactions over time and relate them to thoughts expressed by the subjects as they completed the task. Retrospective analysis by the participants was not employed so this study only begins to uncover how physical manipulation structures thought. As this study was largely exploratory, the primary focus of the analysis was to identify the possible kinds of physical interactions exhibited by the designers and then distinguish them from non-designers.

Similar design research methods are used to identify different types of design expertise, to establish criteria for measuring creativity, and to provide empirical support for developing new design tools (Gero and McNeill, 1998). Protocol studies in general have led to novel

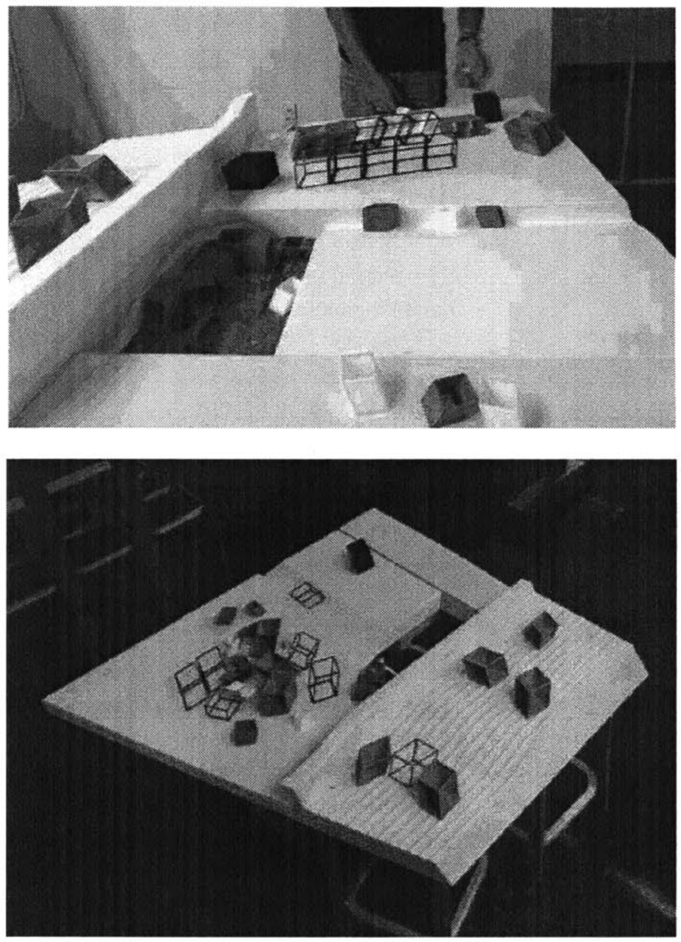
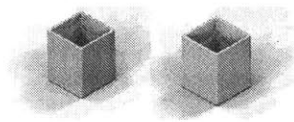
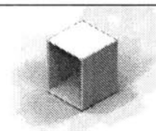
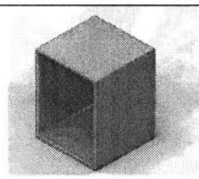
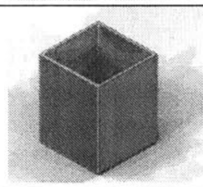
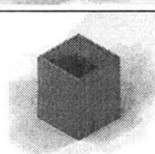
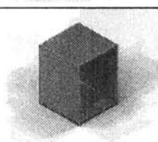
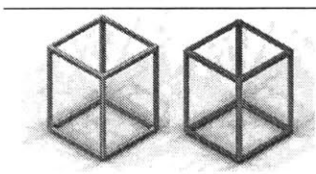
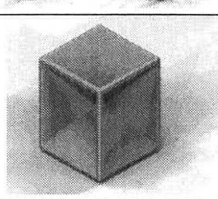


Figure 4.2 The site model for the pick and place study was a painted wooden model with a variety of surfaces, textures, and elevations.

Table 4.2 Block type descriptions and counts

Block image	Description	Count	Dimension
	Blue, green 2 square open-faces ¼ scale	5 blue 6 green	1.25 in^3
	Yellow 2 open-face parallelograms ¼ scale	6	1.25 in^3
	Black 2 open-face parallelograms 1/2 scale	1	2.5 in^3
	Black 2 open-face squares 1/2 scale	1	2.5 in^3
	Red 2 open face squares 1/3 scale	4	1.45 in^3
	Red 2 open-face parallelograms 1/3 scale	5	1.45 in^3
	Black, Red Wire frame 1/2 scale	7 black 1 red	2.5 in^3
	Blue Solid with indents at centroid 1/2 scale	8	2.5 in^3

formalizations of the design process and expanded models of design cognition by framing action as the unit of design analysis (Dorst and Dijkuis 1995).

Video and audio was captured from above the site model (Figure 4.4). Each video was watched numerous times and manually coded based on the coding scheme as described below. Audio was transcribed for each subject. See Figure 4.5 below for an example verbal protocol. Photographs were taken throughout each subject's design session to document the dream house from different points of view.

4.8.1 Coding Scheme

As this was a novel analysis of the interactions exhibited by designers and non-designers in a physical model-making activity our coding scheme focused on the techniques of their physical manipulation of the blocks. Using video-based protocol analysis with the thinking aloud method we devise a novel coding scheme of the participants' actions over time and relate them to their thoughts expressed during the task.

More comprehensive coding schemes have been developed by researchers to identify design actions in sketching activity (Suwa and Tversky, 1997). Suwa, Purcell, and Gero develop four kinds of cognitive actions for their analysis of sketching: Physical, Perceptual, Functional, and Conceptual (1998). Physical actions include acts of drawing and looking and, in their study, were coded by watching the video footage. Perceptual, Functional, and Conceptual actions were interdependent with the physical actions and involve attending to features, associating features, and setting up goals, respectively. Since this requires that the subject say this is what he is doing coding these types of actions requires retrospective reporting.

Our coding scheme was developed through theoretical discussion and intensive analysis of the video protocols. Each video was watched repeatedly and manually coded following the completion of all the experiments. I developed many iterations of the coding scheme before settling on the one described below, e.g., see Kirsh and Smithwick, 2015.

4.8.2 Analyzing model making

In the current work, I am interested particularly in how physical action in model making drives design thinking and in what ways this may differ between experts and novices. Other researchers have studied this topic and therefore it is good to build on their work. Looking more closely at the kinds of physical actions defined by Suwa et al (1998) (also used by Kavakli and Gero 2002), however, I find their action types ill-suited for describing possible material interaction in model making. They distinguish these seven action types:

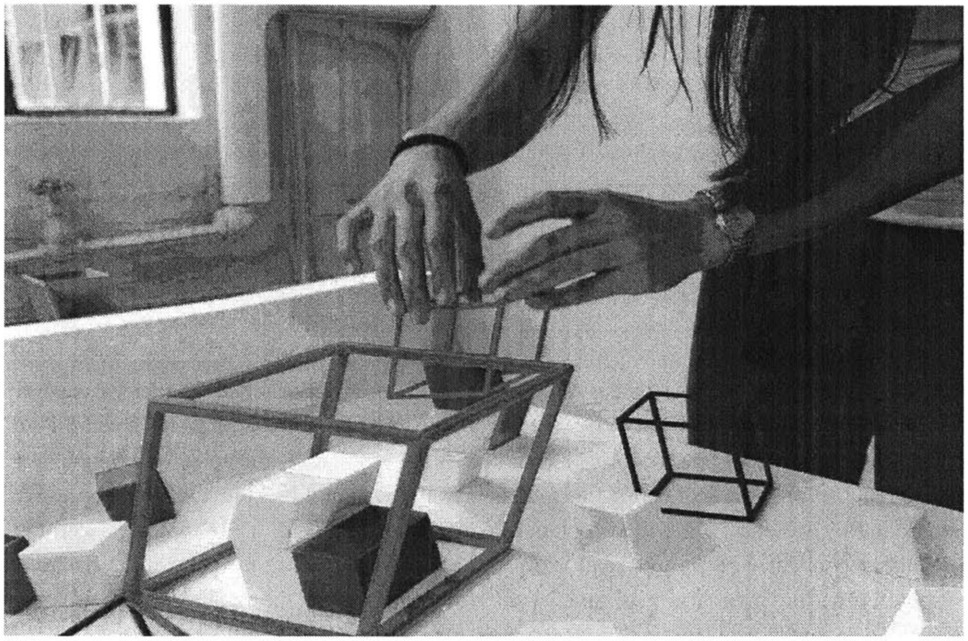


Figure 4.3 A variety of parallelepiped shaped blocks to interact with were provided for the experiment setup.

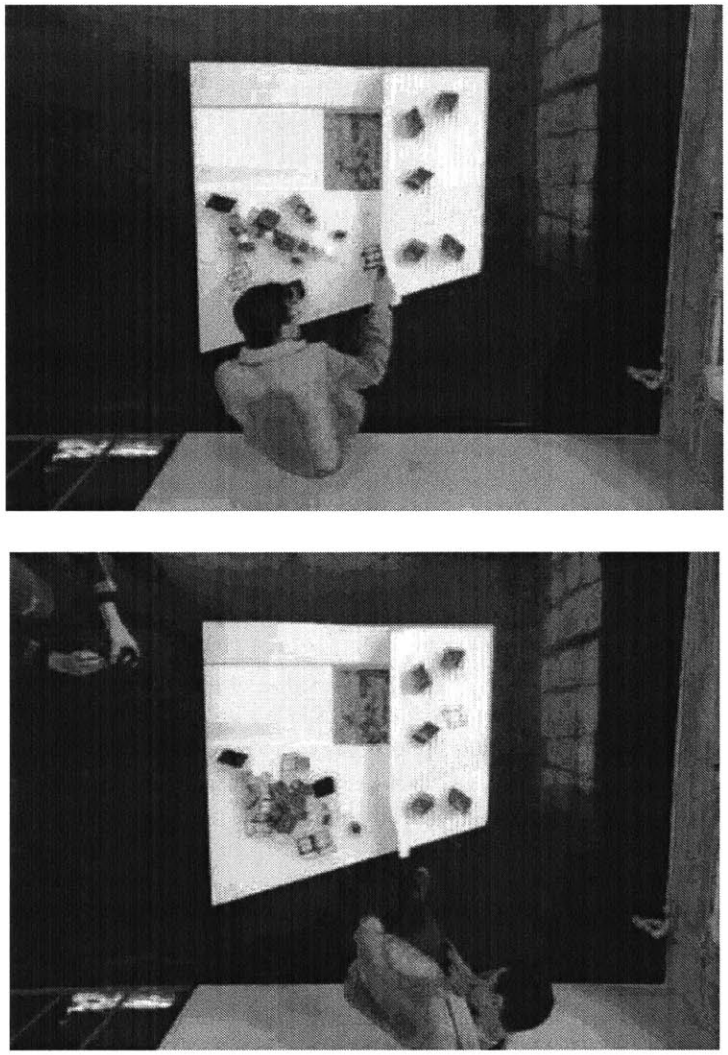


Figure 4.4 Video stills of a experiment participant interacting with blocks on the site model.

- Revise the shape, size or texture of a depiction
- Create a new depiction
- Trace over a depiction on same/new sheet
- Depict a symbol
- Write sentences or words
- Look at previous depiction
- Move a pencil/depiction

In physical model making one does not draw depictions, trace over depictions, make symbols, write sentences, or move pencils. One may perform these actions in the course of making a model, e.g. to depict a shape to be cut out of paper, but this would be a sketching action *plus* some other physical action. Strictly speaking, model making means working with material in hand. Therefore, the actions possible depend largely on the material, opening up a wide range of interactions: folding, twisting, laminating, stacking, sorting, cutting, milling, pouring, and so on. In addition, model making commonly involves the application of skill and technique with tools diverse as knives, drill presses, laser cutters, and 3D printers. This makes model making as a general activity cumbersome to analyze in terms of a finite set of physical actions.

This complexity may explain why little research has been conducted on model making as a kind of physical thinking process. Studies that do examine model making are highly constrained. For example, to explain the benefit of hands-on model making in engineering design, Lemons et al (2010) have participants construct models with Lego bricks. In addition, their analysis is limited to the verbal protocol only; they do not code the different physical actions possibly observed such as joining, disjoining, rotating or sorting bricks.

4.8.3 Pick-Transform-Place Framework

In model making activity one works with material objects and arranges them in different relationships that can be called configurations. Different materials can be configured in different ways. When working with blocks, the making of configurations can be characterized as a three stage process: picking, transforming, and placing the blocks. Picking and placing stages are defined by their location in the world, either within a configuration or on the site; the transformation stage is defined as the operation that happens after picking and before placing. When working with blocks only rigid transformations are possible: rotation and translation. Transformation can also be defined by its duration of time. For example one may quickly rotate a block in his hand, or one could spend a significant amount of time studying its features.

4.8.3.1 Primitive Interaction Types

Based on the pick-transform-place framework I construct four primitive interaction types: **adding** blocks to a configuration, **subtracting** blocks from a configuration, **modifying** blocks within a configuration, and **relocating** blocks across the site. Each of these four types is defined by the locations of the picking and placing actions as identified in Table 4.3 below. For each participant I counted each action type as an instance and as a nominal duration of one second. I observed this to be an accurate measurement of the primitive interactions (likely this was due to the size of the site upon which they were to build); in the special case *inspect-interactions* (described below) where the subject took more time, e.g. to look more closely at a block, I counted the actual duration of time.

4.8.3.2 Inspect-Interactions

Within the interactions, I do not distinguish between the quality of transformation, i.e. degree of rotation or distance of translation; however I do account for a variation of interaction in which the participant introduces additional transformation: bringing the block close to their face. I call this *inspection*. Each interaction type has a special case of this, e.g., *Inspect-Add*, *Subtract-Inspect*, *Modify-Inspect*, and *Relocate-Inspect*. I counted each of these types as an instance and as an actual duration in seconds.

Table 4.3 Definition of Interaction types by pick and place location

Interaction Type	Pick location	Place Location	Description
ADD	Site	Configuration	Participant adds block from the site to the configuration
SUBTRACT	Configuration	Site	Participant removes block from configuration and places on site
MODIFY	Configuration	Configuration	Participant adjusts block within configuration only
RELOCATE	Site	Site	Participant moves block across the site

4.8.4 Body Movement

I account for 'looking actions' differently than previous coding schemes. I do not account for *what* the participants may be looking at or attending to, such as a particular block or relationships between multiple blocks in a configuration. I assume they are looking at these things in the course of interacting or inspecting. Rather, I account for changes in the participant's position, or body movement in relation to the model. For example, a participant may reorient his head to see a different view within the model or reposition his full body to see another side.

4.8.5 Interaction Sequences

While developing the interaction types and through analyzing the protocols I noticed patterns in the sequence of interactions over time. Some participants tended to group particular actions together and some interaction types were coupled together more than others. To capture this behavior with my framework I developed three types of interaction sequencing: Consecutive, Compound, and Coordinated. See Table 4.4 below for all interaction sequence definitions.

Consecutive interactions involve three or more identical actions in a row. For example, Add-Add-Add actions I count as one kind of Consecutive interaction. Compound interactions occur when the Place location of one interaction becomes the Pick location of next action. For example, when a subject Adds a block to a configuration and without putting it down, does a Modify action, I consider this as a Compound interaction. Coordinated interactions are two-handed action.

There are two types of Coordinated interactions: Synchronous and Asynchronous. For example a subject may modify a block using both hands. This would be a Synchronous interaction, using two hands to do the same action. Asynchronous interaction is doing two different interactions with two hands.

4.8.6 Segmenting Interaction Sequences

From the protocol alone I was not able to determine how to segment the interactions as sequences. For example if the sequence of interaction was: add-modify-subtract-add-modify-subtract, I had to determine how to divide this. Did this count as [add][modify-subtract][add-modify][subtract] which would be one Add action, one Test:Reject Interaction, one Test:Affirm Interaction, and one Subtract action? Or, did this count as [add-modify-subtract][add-modify-subtract] which would be two back to back Test:Decline interactions? To determine this I re-watched the videos to look for where the precise point of block release was and importantly, where the actions flowed together. Another consideration to make was to determine how to count consecutive interactions that grouped greater than three actions together. For example in Figure 4.5 at the beginning of the protocol there are twelve Relocate actions in a row. I counted this as four separate Manage interactions.

1:05	Relocate
1:06	relocate
1:07	relocate/relocate
1:09	relocate/relocate
1:11	relocate-inspect/relocate-inspect.3
1:15	relocate/relocate
1:17	relocate
1:20	relocate
1:29	relocate
1:30	relocate
1:44	relocate
1:49	relocate
1:50	*RW: I'm just looking at the different kinds of pieces I have right now...and maybe I'll assign each piece a different role in the house.*
1:51	relocate
1:51	relocate-inspect/relocate-inspect.9
2:02	add
2:07	add-inspect.8
2:12	*RW: these aren't necessarily walls, but maybe just open space*
2:21	subtract
2:22	add-inspect.2
2:25	add
2:31	modify.2
2:36	relocate
2:38	relocate
2:40	modify-inspect.7
2:48	subtract
2:55	Add
2:59	*RW: is there anything to be said about the surroundings?*
3:06	*DS: you tell me...up to you*
3:15	Add
3:16	Modify.2
3:21	Add
3:22	Add
3:27	Add
3:35	Add
3:39	Modify.2
3:41	Modify.1
3:45	RW: *it'd be kind of cool to have a wall of windows along the side of the house...maybe the south facing side where there's a lot of sun.*
3:46	relocate
3:51	relocate-inspect.8
4:01	relocate

4:04	relocate
-	-
4:50	*RW: maybe I'll use these as passage ways...hallways*
4:53	relocate
4:55	relocate
5:01	relocate-inspect.3
5:04	relocate
5:06	Add
5:10	Modify.2
5:12	subtract
5:14	relocate
5:16	Add
5:17	Modify.3
5:20	relocate
5:22	subtract
5:28	add
5:30	Modify.2
5:33	Add
5:40	Modify.1
-	-
7:01	Add
7:09	add
7:18	add
7:20	relocate-inspect.2
7:26	relocate
7:28	Add
7:32	Add-inspect.12
8:57	Add
9:01	Add
9:07	Add-inspect.4
9:15	Add-inspect.5
9:22	relocate
9:23	Modify.1
9:27	Add
9:29	Modify.2
9:36	Add
9:37	Modify.6

INTERACTION SEQUENCES KEY
MANAGE
ASSEMBLE
DISASSEMBLE
EXPLORE
TEST:EJECT
TEST:AFFIRM
TEST:REJECT

Figure 4.5 Example of a participant's action protocol with color-coded Interaction Sequences.

Table 4.4 Definition of Interaction Sequences

Interaction Sequence Type	Name	Interactions
CONSECUTIVE	Manage	Relocate-relocate-relocate
	Disassemble	Subtract-subtract-subtract
	Assemble	Add-add-add
	Explore	Modify-modify-modify
COMPOUND	Test:Reject	Add-Modify-Subtract
	Test:Affirm	Add-Modify
	Test:Eject	Modify-subtract
COORDINATED	Synchronous	Modify/modify, e.g.
	Asynchronous	Add/modify, e.g.

4.9 Why a dream house?

A dream house is an architectural program accessible to both architects and non-architects; most people at some point have imagined what their dream house might look or feel like. Since the subjects had varied in experience in architectural design, from none at all to 8 years practice, it was important that the task be easily understood and accomplishable by non-designers, yet interesting enough to engage the expert designers. A dream house is something that many people, not just architects, have thought about so it allows the non-architects in the study to explore their own creative ideas.

4.10 Why picking and placing blocks?

Block manipulation is a creative activity in which design thinking can take place. I liken the manipulation of blocks to Schön's concept of a 'move experiment' in the see-move-see framework of design. The designer first sees the block one way, then makes a move on it such as picking it up, rotating it, and then placing it down, and then he can see it in a different way. Through interaction different seeings are possible.

Although by constraining our experiment to arranging blocks I do limit the possible architectural forms (which more than one architect pointed out), I also (beneficially) constrain possible material manipulations to an activity that does not require technical skill or specialized training. If for example we gave the task of designing a dream house on a computer, I would risk a result that simply reflected prior experience with the software. My study is intended to reveal material interaction in the most basic sense.

However, since arranging blocks is not a common design process used by architectural designers it should be questioned as to what can be gained by studying such an abstract activity. For example, sketching is a much more common design activity that is analyzed in design research (Suwa and Tversky 1997). With this study I wanted to look at more physically engaging activities in which architectural design concepts could be explored by the participants. Although arranging blocks is a highly constrained form-making activity it still offers opportunity for architectural design exploration. Blocks offer limitless configurations and spatial relationships. Repetition, scale, adjacencies, view-taking and massing can be explored with the blocks and these are important architectural concepts.

Another reason to study picking and placing blocks is that it reduces task complexity making analysis feasible for the scope of this project. This could have been a paper folding exercise or chip board sketch model making exercise but those present prohibitively complex interactions with multiple tools, techniques, and materials to account for. In addition, I also limit possible operations to that which may theoretically be performed by a robotic manipulator arm: picking, transforming (rotating and translating) and placing blocks. As one of my objectives is to consider how a robotic manipulator arm may be used as a creative partner in early stage conceptual design my work here sets the stage for informed speculation.

4.10.1 Why parallelepiped blocks?

Parallelepipeds are like cubes that have been sheared with the result that some of the square faces become parallelograms. The blocks used in this study have been sheared in two axes giving the blocks two square faces and four parallelogram faces. Figure 4.6 below compares the parallelepiped shape with the cube under identical rotations.

Parallelepipeds were given instead of cubes for two reasons. First, they are simple enough for most participants to use as a construction unit. They are not overly complicated shapes that may result in more dramatic forms, but would be likely too difficult to understand in limited time and use as a quick building block. They stack together easily much like cube blocks would stack. Secondly, the parallelepiped form offers nice surprises to the designer. While the parallelepipeds are simple physical forms, perceptually they are complex. From many vantage points they look like cubes (for example, see the third block from the left in Figure 4.6). This sets up an expectation that it will behave like a cube, but when interacting with them the block presents unexpected changes in shape that are skewed and tilted in surprising directions. This familiar yet unpredictable shape is well suited for a dream house design task.

4.10.2 Symmetry lessons for surprising interactions

What makes a parallelepiped the interesting shape that it is has to do with its low but uniquely placed symmetry. Many objects have low symmetry or none at all. At one extreme, a blob form is asymmetrical and therefore there's no expectation that it behave in predictable ways. When you rotate it you expect to see it change. No surprise there. At the other extreme a sphere has infinite symmetry. When you rotate it you expect to see no change at all, ever. Otherwise it wouldn't be a sphere. Again, no surprise there.

A cube has high symmetry but not infinite. It has 48 symmetries, making it usefully predictable under many transformations (See Figure 4.7). The short hand for determining symmetry of any regular solid is to multiply the number of its faces by edges per face by 2. A cube therefore = 2*F*E = 2*6*4 = 48. The parallelepiped used in this study has only 3 symmetries: one reflectional plane, one rotational axis, and identity (itself). The result is a shape that looks like a cube but changes unpredictably under transformation.

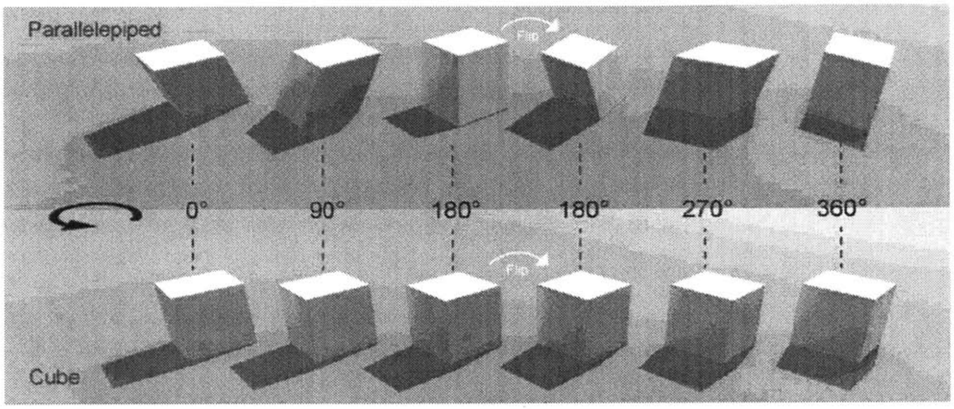


Figure 4.6 Comparing the parallelepiped with the cube. Shading changes unpredictably along with face shapes on the parallelepiped under rotations while it remains constant on the cube under the same rotations.

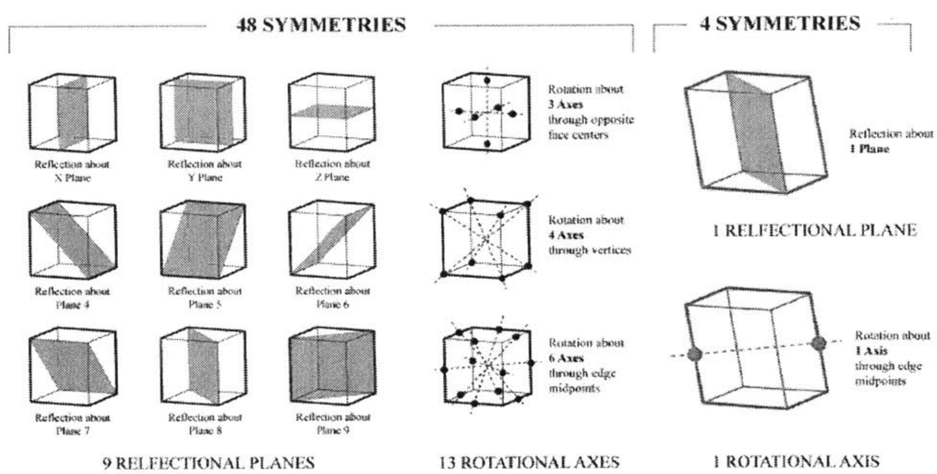


Figure 4.7 What accounts the surprising nature of the parallelepiped is its low symmetry. Here is a comparison of the rotational and reflectional symmetry of the cube and parallelepiped.

CHAPTER 5

RESULTS

Kinds of Designerly Interactions

"Movement is life...A great deal of our perceptual knowledge comes from movement, both our bodily movement and our interactions with moving objects."

-Mark Johnson

5.1 Nine Dream Houses

In this chapter I present the results from the thesis project. I first present the verbal protocols, photographs of the participants in action, and images of their dream house models that were created. Following this I present the interaction data based on the coding scheme described in Chapter 4 and their analysis. I conclude this chapter with a discussion of the observed differences between expert designers, novice design students, and non-design students.

I characterize the experts' behaviors as a kind of designerly material interaction. To restate the hypothesis: given an early stage exploratory design task requiring physical material manipulation, I will observe differences in the kinds of interactions and body movements exhibited by experienced architects from those exhibited by novice students and non-designers.

The ultimate analysis is focused on nine participants' body movements and interactions with the blocks as they created their dream house. These nine were selected from an original seventeen participants that were observed based on a number of factors. First, was the amount of information provided by the participants: some of the participants did not voice out loud many thoughts during their design session nor answer the researcher's probing questions with much depth. This made it difficult to analyze their verbal protocols. Second, some of the participants did not follow all of the rules of the design task. For example, one architect only designed one bedroom of his dream house when the task was to design the house in its entirety. While this perhaps does indicate an approach to problem solving by breaking it down into smaller parts, this makes comparative analysis difficult. Another subject used blocks that were not a part of the original set given. I excluded these participants from the analysis and ended up with three participants from each group to give an equal representation in the study. I also wanted to analyze a range of designs including ones with many blocks vs few blocks; strict placement vs loosely organized; and designs that were constructed over long periods of time vs short periods.

By limiting the number of subjects included in the analysis this gave more opportunity for in-depth qualitative analysis though it reduces the ability to make substantial statistical claims. Many design protocol studies are done on small groups and individual designers. Together these qualitative studies help paint the fuller picture of design thinking. Furthermore, this work sets the stage for larger scale studies. As such, the findings presented should be taken as being suggestive of certain qualities of what it means to have designerly interactions with material objects.

5.1.1 Overview of Findings

In the course of this project I have observed a variety of body-material interactions resulting in a variety of dream house designs made with the blocks. I was surprised by many of the results. Where I can, I call attention to any observed differences across the three groups of participants, especially if there are trends from the experts, to the novices, and to the non-designers. Such trends are telling of both learned and inherent designerly ways of knowing. In many cases I also observed differences within each of the groups which suggest that a larger study would be beneficial.

The interaction results do confirm part of the hypothesis – that the experts perform epistemic actions more so than the novices and non-designers. However, this is only the case by considering very narrowly what constitutes an epistemic action in a design task. There were many actions performed by the novices and non-designers that might be considered epistemic as well. For example, sorting the blocks at the beginning of the task by color or type, or closely inspecting features of individual blocks by picking them up off the surface and rotating closely to the face. Both of these kinds of block interactions take the subject further away from completing the task of assembling the dream house but may help in understanding the blocks as construction units. These actions may make it easier to determine how the blocks could fit together in different relationships. For example, if you sort all the red blocks, blue blocks, and green blocks and organize them so their orientation is the same, this would make it easier to see how you could use the red ones for one part of the design and the green ones for another part of the design and so forth.

The interaction results show that the novice and non-design student perform such organizing actions more often than the expert participants. Why is this the case? Are these the only kinds of epistemic action? Perhaps, but in this case I would not consider them to be *designerly* epistemic actions. This perspective suggests that the assembly of configurations was not the goal that the architects were pursuing in this design task. Analyzing the verbal protocols is revealing to help understand what the experts were pursuing in the task.

In analyzing the four primitive interactions—Add, Subtract, Modify and Relocate—although I did find a wide range results in terms of the number of actions for each subject, I observed many trends from experts to novices to non-designers. It was in analyzing the sequence of interactions that I found more interesting results across the three subject groups. In this case I found trends in Manage, Assemble, and Explore interaction sequences. The architects tend to perform less Manage and Assemble sequences and perform more Explore interaction sequences. This suggests that the architects are not just constructing preconceived ideas but are rather using the blocks to think about possibilities. There are also differences in the structure of interactions. Architects tend to group their behaviors into longer sequences working with a single block for longer periods of time. This in turn suggests that the architects think more deeply about the effects of manipulation on the blocks.

Together these findings tell us that when working with physical media, experienced architectural designers do indeed behave differently when compared to novice and non-design students. These differences can be characterized as epistemic actions that help exploit material properties and reveal spatial relationships.

5.2 Verbal Protocol Analysis

The participants were asked to voice out loud any of their thoughts while constructing their dream house with the blocks. While some subjects were more articulate than others, I was able to find qualitative differences between the three subject groups. Below I highlight quotes that characterize each group.

5.2.1 Novice architecture students

Typical of the design students, one novice, MR, described her process as one of finding blocks to represent typical house-hold elements:

> "I'm using this [red block] as the entrance...and I'm going to use these [green blocks] as the grass and flowers...and these [wireframe blocks] will be windows. These [the blue blocks] look heavier so those will be the big walls...like the frame of the house."

Looking at MR's model (Figure 5.1, top) one can see that she was using the blocks to create a perimeter of walls and windows around an interior space. The blocks were 'things' like windows and walls, and these could be used to demarcate household spaces like rooms or courtyards. MR also considered how the blocks could relate to one another spatially, saying:

> "It'd be cool if these [blocks that she picked up] were mirrors of each other" (Figure 5.1, bottom).

In this sense MR was thinking more abstractly about the blocks in how they could be used to construct a formal geometric relationship. Momentarily the blocks stopped being a room or a wall and became an architectural material with inherent properties.

Another novice design student, JC, had a similar approach of creating an interior space with perimeter blocks, commenting that:

> "Because these are such abstract and odd forms you can say that they're whatever."

She continued,

> "Right now I'm building rooms back off the courtyard...so these are like rooms but also like walls."

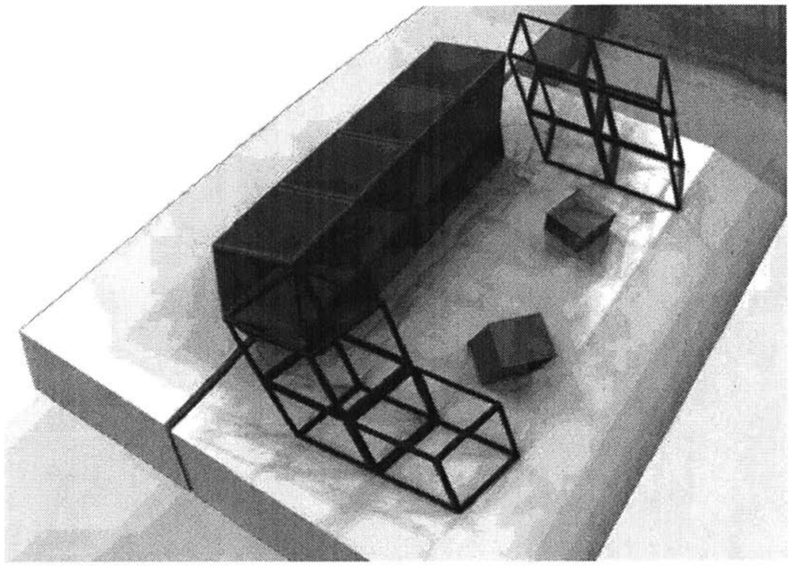


Figure 5.1 A perimeter wall of blue blocks and windows with wire frame blocks is created, left; Subject MR picks up and compares two blocks, looking to make mirror relationship, right

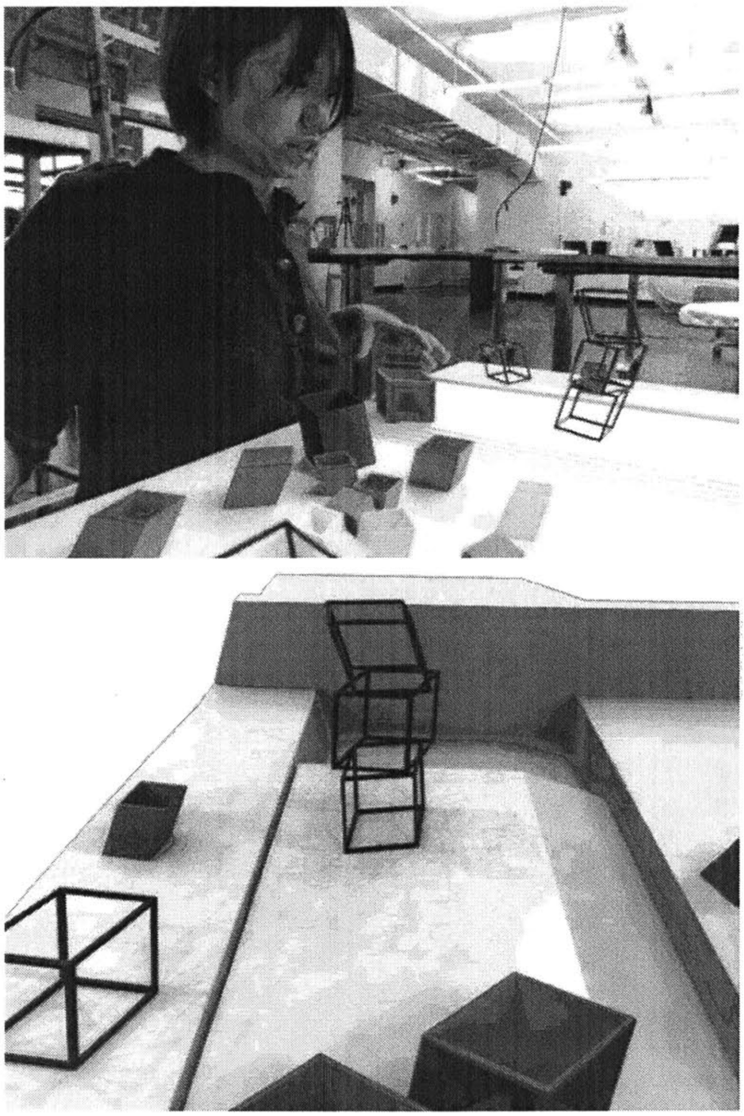


Figure 5.2 Noticing that the blocks were not regular cube shapes, subject JC decided that they (the wireframe blocks) didn't need to be flush when assembled together

For JC the blocks haven't taken on as strict of a definition as the blocks did for MR, but she has defined what they might be according to house features, like walls and rooms. This novice also talked about the shape of the blocks and how that might affect how they are assembled together:

> "What's interesting about these is that they're all parallelograms so nothing will be a boring rectangular form. So maybe they don't need to be flush" (Figure 5.2).

JC described her design as in terms of the limitations of the blocks provided:

> "A nebulous shape of a building that contains spaces inside it that you can't really explore with these blocks."

She also commented about how her body's position in relationship to the model impacted her design. Towards the end of the session she realized that she had been looking at it from the same vantage point the entire time. When she moved her position it became clear that the model was unintentionally sloping up on one side.

The third novice, JG, talked about the relationship between her dream house and the site model:

> "I see this [area of the site] as a more natural landscape...maybe this is a street...an urban flat space. Maybe my house will have a street in front and a park or forested more natural area that I would really value. So I'm trying to connect the two...maybe I could knock a hole in the wall or maybe just go over it" (Figure 5.3).

In describing her process she identified a design goal of connecting two different spaces on the site model. She also came up with some strategies for reaching the goal...of building over or through the wall. In attempting to go over the wall with the blocks the novice commented on how dealing with the three-dimensionality of the blocks was challenging:

> "I realized especially when I dealing with shapes I'm not familiar with...if something's in 2D I can imagine it in my mind...but if its 3D I don't know what kind of problems I'm going to have so I feel like I can't prepare for it...I just have to do it."

For JG working with physical media is expressly different than working in two dimensions, presumably sketching or drafting activity. Relationships between material objects are harder to predict in advance and actions are needed to explore the potential. Overall, the novice design students seemed to go back and forth between using the blocks as rooms or features to be assembled and using them as abstract material to be manipulated. The latter is something I find more typically in the experienced architects' process.

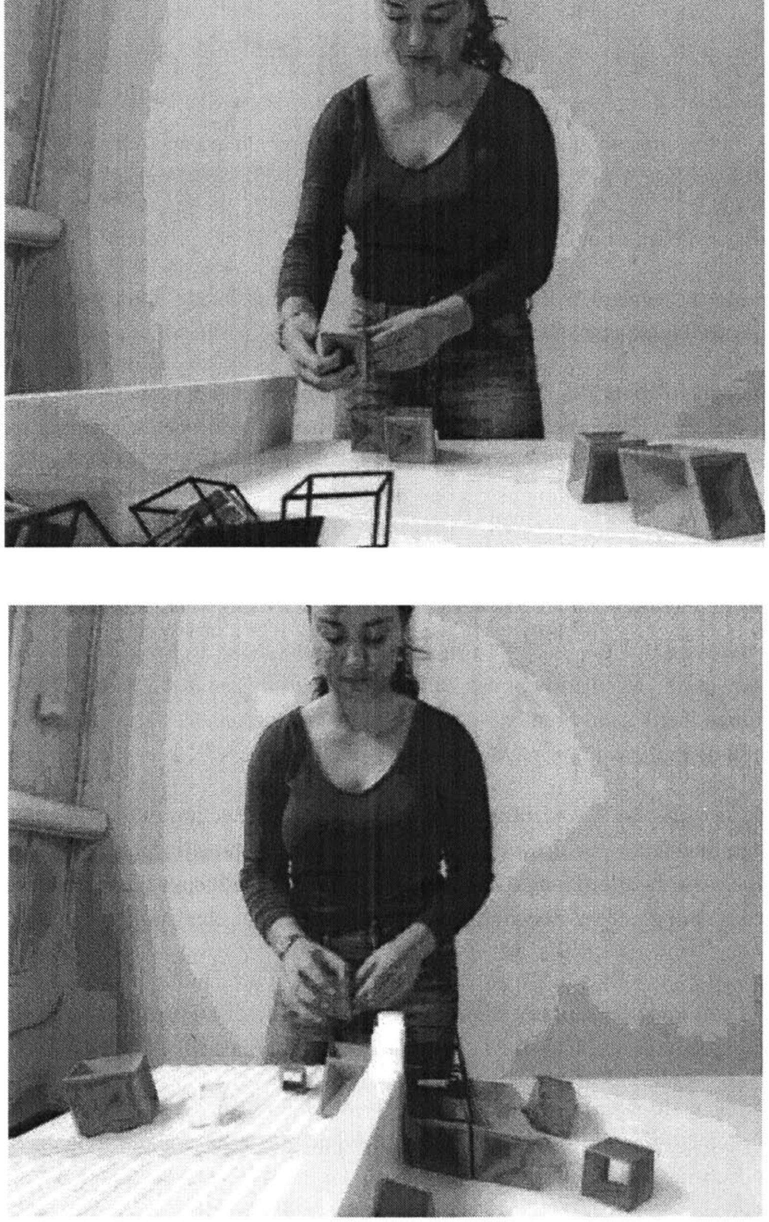


Figure 5.3 Subject JG inspects the blue blocks and then builds her dream house over the wall

5.2.2 Architects

Experienced architects had a slightly different approach than the novice students. Some of the architects commented on the effect of moving shapes around to explore the spatial relationships between the blocks. For example, one expert, RM, remarked very early on in the design session about the potential embedded within the blocks, saying:

> "I like that these create an 'outdoor/indoor'...a kind of exterior spatial definition and an interior spatial definition...it's super strong...and you don't have to do much to let them do that...which is nice" (Figure 5.4).

The notion of outdoor/indoor space is a learned device in architectural design practice. It's an abstract way, meaning it doesn't' refer to any specific architectural room or feature, of seeing and dealing with material objects that can help give shape to potential spatial relationships. Furthermore, he pointed out that the blocks themselves provided the indoor/outdoor condition so it wasn't necessary, as some of novice design students did, to create a perimeter of blocks to delineate a space. The blocks did this already.

With this realization inherent to the blocks the expert developed a design concept early on and was able to give himself a further constraint by working with a limited set of blocks. He said:

> "I didn't intermingle the blocks because I like the way the red ones fit together. It's more controlled for me."

One notable difference between the architects and novices is exemplified by what RM said about using the blocks as rooms or specific features. He was explicitly not thinking about the blocks in terms of household features:

> "I can't go through it and say what's my bedroom, what's my living room...but as a plain figure I like it and can imagine it occupied in many ways."

In other words, RM was aware of how one might immediately begin to think about a house in term of its component parts, especially when working with material, blocks, that suggests such parts. He avoided this approach and focused instead on seeing the blocks as a 'plain figure' which could become any number of things. It is the potential afforded by the blocks that RM was interested in exploring with the blocks.

Another expert, SK, also started off his design session by exploring the blocks' properties. He succinctly stated:

> "Using the blocks, I am creating face-matching walls."

He was giving himself a formal geometric constraint – joining the blocks face-to-face – and seeing what relationships were possible (Figure 5.5). Similar to RM, he was not demarcating

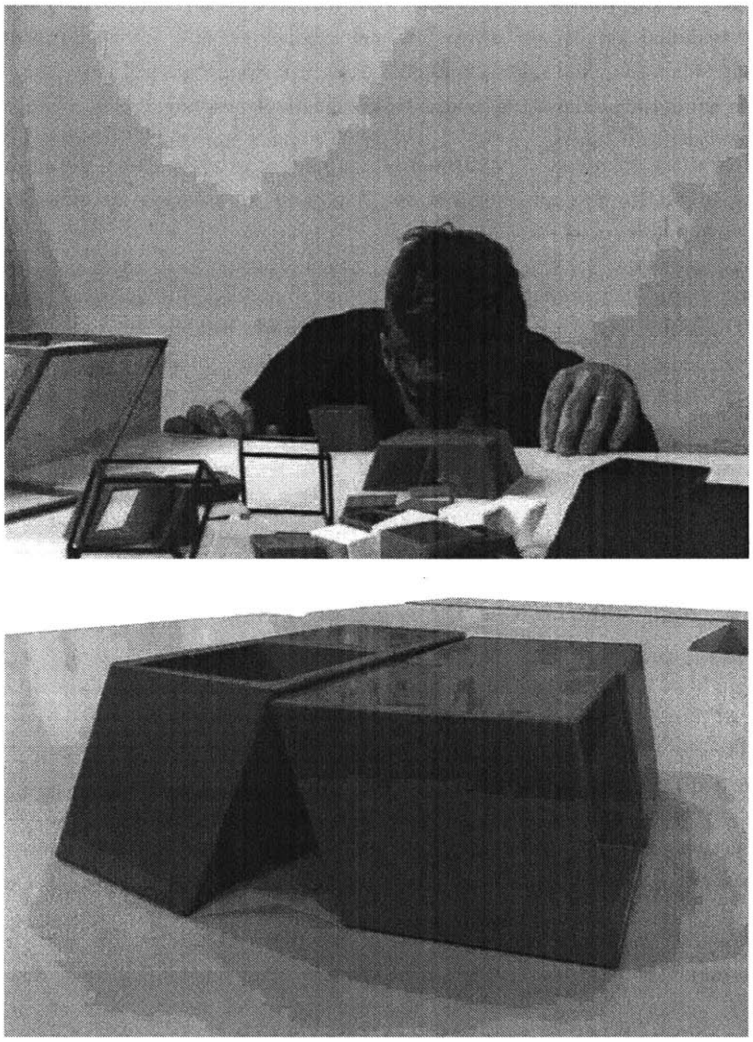


Figure 4.4 Subject RM examines his design close up to see 'indoor/outdoor' relationships

space with the blocks, but rather exploring how the blocks could fit together as a figure. While exploring these relationships he developed two particular design goals:

> "I'm looking for...what I'm hoping this will be is some kind of dividing wall...or on this side I want to have an elevated mass...held up by three [blocks]...because I want the idea of danger to be present."

Here, SK is taking a slightly different approach than RM. He is creating a narrative that is expressed through the blocks' spatial relationships. This narrative is not attached to anything particular about a house; it is just a generative device that the blocks can help convey. The idea of danger became an experiential quality that he further articulated in descriptive terms:

> "So here is a mysterious figure rising out of the ground...supported tenuously."

SK was creating a figure-ground relationship that evoked a particular experience one might have in his dream house. He was not thinking about the arrangement of rooms with the blocks, but rather how the blocks themselves could be arranged. The material and its spatial qualities was the object of his thinking. And using the dramatic narrative he gave his idea some color.

SK noted that he was working with a limited material and he therefore had to develop another advanced device to support his design. He said:

> "What I want to do with this one [a new configuration of blocks]...since there is no long linear piece...what I can say...is that I'm creating a visual connection between these two volumes."

His 'visual connection' between blocks is important to distinguish from the approach taken by the novices. The novices created space in between multiple blocks that they often identified as courtyards. Here, the courtyard space was completely and literally surrounded by blocks that were physical touching each other. On the other hand, with SK's approach, the space was only implied and was achieved through a particular alignment of blocks across a distance. With his approach, one had to 'read' the geometrical language of the blocks to visually make a connection through space to see the space.

Architect BC took a different approach than the other two architects (Figure 5.6). He immediately referenced the use of discrete blocks to an historical 'modernistic' approach to designing:

> "The kit of parts is a modern way of thinking about how can you mass produce elements that you then re-configure together to produce different solutions."

With this in mind he thought of a famous modernist architect, Le Corbusier, and tried to design within his 'style'. He used the wire frame blocks to create a "pilotis" which is a frame

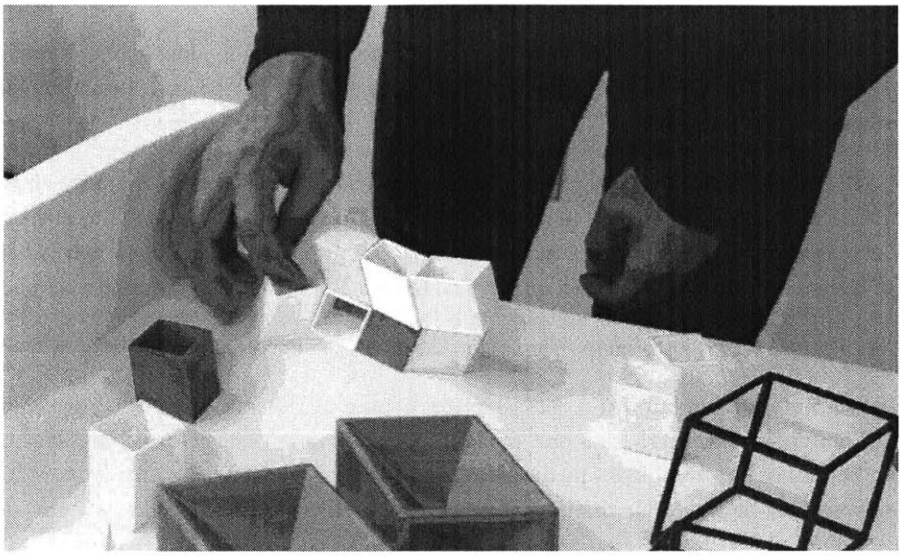


Figure 5.5 Subject SK created "face-matching walls" to explore relationships between the blocks.

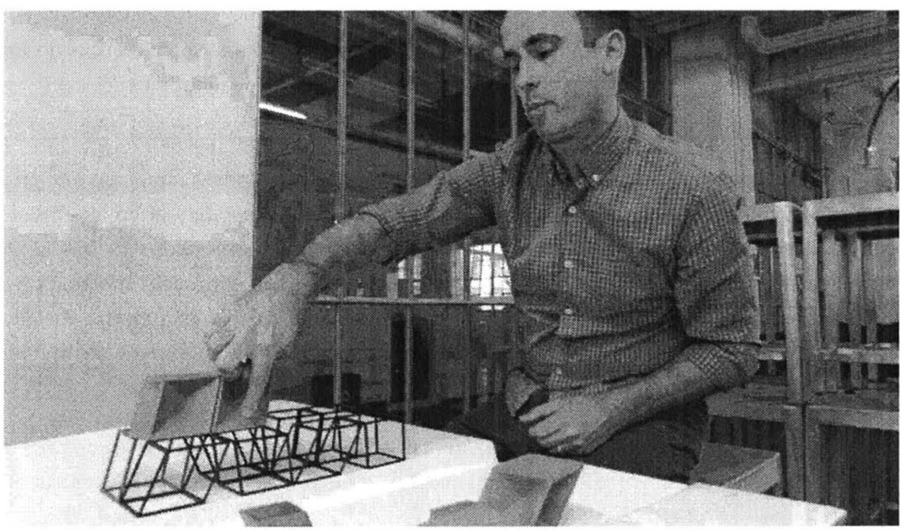


Figure 5.6 Subject BC made an historical reference to Le Corbusier's strategy of creating a *pilotis* for building his dream house with the blocks.

structure to lift buildings off the ground. The framed style blocks served this purpose well. Moving forward with this approach the participant voiced his process as having to:

> "...invent a problem for myself to resolve."

Presumably, this was a geometric problem to resolve because he added:

> "I would like to scale these blocks so they align. But I can't do that because I have a fixed set of parts. So I'm just going to have a gap in my building."

Block alignment and spacing were important in constructing his pilotis. However, he commented that the blocks were too limited for his typical design process:

> "I would never use a kit of parts in my own work. I would design the goal and then discretize it down to unique units...so this is out of my comfort zone to use fixed parts."

Overall, the architect participants talked very little about a 'house' with certain rooms and more about abstract experiences and spatial qualities that were possible to explore with the blocks. Their process can be characterized as working with the material in hand and exploiting its properties to develop architectural concepts but not necessarily architectural solutions. They often employed devices such as figure-ground or visual connections to constrain and enrich their design process.

5.2.3 Non-design students

Surprisingly, the non-design students tended to be concerned with creating the most 'house-like' ideas and in particular were concerned with typical house features such as room layouts or walls. Their designs tended to be very linear in nature which suggests that their thinking was also linear. Participant CY focused on creating a fantasy house that doubled as a rock climbing gym. As she was stacking blocks on top of each other to produce a tall structure she noticed that the block edges themselves could serve a particular function:

> "The first time I used only the outsides [of the blocks]...the smooth side...and I thought that would suck [for rock climbing] so I wanted there to be holds everywhere" (Figure 5.7).

By staggering the blocks slightly she could achieve her goal of creating ways to climb the blocks. Thinking of particular household features was also a concern for her:

> "And obviously because it's my dream house each one of these [blocks] is a room."

Another non-design student focused on how the house would be situated on an imaginary site to allow views from particular rooms:

> "So right now I'm imagining this [open area on the site] as the ocean and I'm orienting the rooms so that you can see out into the landscape...so these are two living spaces like lounges or a dining room and these can be like bedrooms" (Figure 5.8)

He was concerned with the house as an experience of moving from room to room:

> "They're [the blocks] not aligned, which started out by accident, but I think it would be kind of cool as an idea, if not for my actual house, if you had to navigate through this convoluted maze of rooms in order to get to this beautiful view."

Through exploration of the blocks he discovered a potential experience that one might have in the house. It should be noted that this is an advanced way of thinking about blocks. It's opportunistic in that the material revealed to him that they didn't necessarily need to be aligned. This is similar to the novice designer who realized the similar property and exploited as a feature of the design. The third Non-design student, RW, had the most practical concerns about his house, commenting that:

> "it'd be kind of cool to have a wall of windows along the side of the house...maybe the south facing side where there's a lot of sun" (Figure 5.9).

In particular, he was thinking about rooms and how to connect them:

> "this is a wide open living room, here's an open hallway on the side of the building...the little blocks I'm treating as hallways and maybe stairs, this is the kitchen, here is a studio...there's bedrooms on the second floor."

The non-design students expressed a wide variety of design strategies and goals. Perhaps the differences suggest that some of the participants had more design aptitude than others.

5.2.4 Limitations of the verbal protocols

I did not segment and code the verbal protocol in specific categories as have many other studies. I made this decision in light of limited verbal data collected and limited scope of analysis. I believe my instructions to the participants were not explicit enough in conveying to them how much they should have verbalized. Also, I believe that concurrent reporting interfered with the participants' ability to interact with the blocks. Most participants had difficulty talking aloud and manipulating the blocks at the same time. Most of the time when participants did talk they would stop working with the blocks or they would fidget with them in their hands, breaking from their previous interactions. This is an interesting observation in itself about the nature of working with physical media. This suggests that working with physical media places larger demands on mental capacity than two dimensional design activity such as sketching. In this case retrospective reporting would be more effective.

Figure 5.7 CY's dream house doubled as a rock-climbing gym.

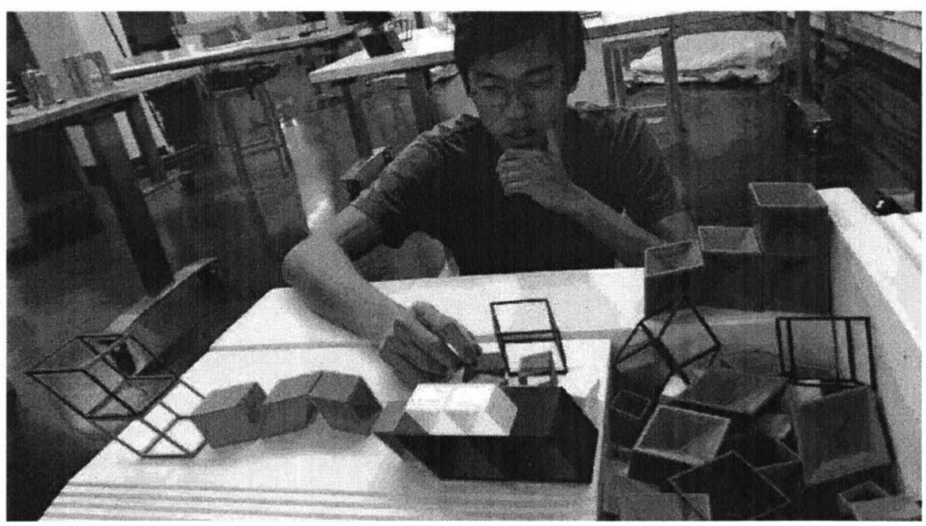


Figure 5.8 FT created a progression of experiences with the blocks

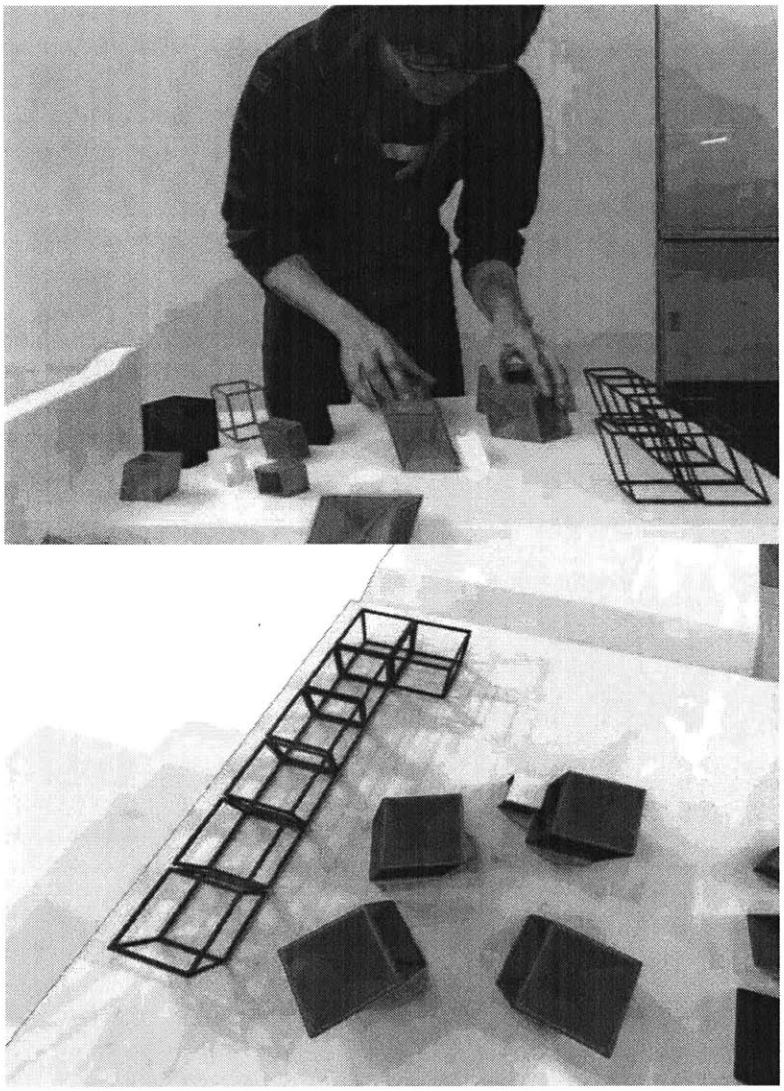


Figure 4.9 Subject RW made more house-like features: a wall of windows with the wireframe blocks

5.3 Dream House Model Analysis

Looking at the design models that were constructed we can also see some differences between the three subject groups. Figure 5.10 shows renderings of each of the subjects' final designs. Each rendering is an orthographic projection of the model. It should be noted that the projection angle was chosen in order to provide the best overall visibility of the blocks in the model. Some of the designs have 'fronts' and 'backs' which in many cases corresponded with the position from which the subject worked on the model; however this is not reflected in the orientation of the renderings. Also it should be noted that the site model is not present in these renderings.

5.3.1 Number of blocks in the design

Architects tended to use fewer blocks in their models than the other two groups. Their mean number of blocks used was 11.0, where the novices used 17.3 and the non-design students used 19.0. What might account for this difference? It was observed that the novice and non-design students would often keep adding blocks to their configuration until the supply ran out, where the architects would seem to identify a limited set, e.g., only the red blocks, or only the wire frame blocks, and just work with those.

Table 4.1 Number of blocks and block variations for each subject

	Architects			Novices			Non-designers		
	RM	SK	BC	MR	JG	JC	CY	FT	RW
Block Count	9	12	12	22	15	22	12	16	29
Block Variations	2	6	2	5	4	9	6	8	8

5.3.2 Using block variety

Architects used fewer variations of the blocks in their models. 10 different variations of blocks were provided to each of the participants (see Table 4.1 in Chapter 4). Two experts only used two variations of the blocks – in one case both were red blocks and in the other case the expert used the blue blocks and wire-frame blocks (Figure 5.10, models E1 and E3). The novice designers used on average 6.0 block variations, the non-designers used 7.3, while the experts used 3.3 block variations on average. I believe this was the case because the architects were able to 'do more with less'. As they expressed in their verbal protocols they would hone in on a particular relationship and explore variations of it. Instead of adding more and more rooms via blocks, they would add more and more depth to their idea via the blocks.

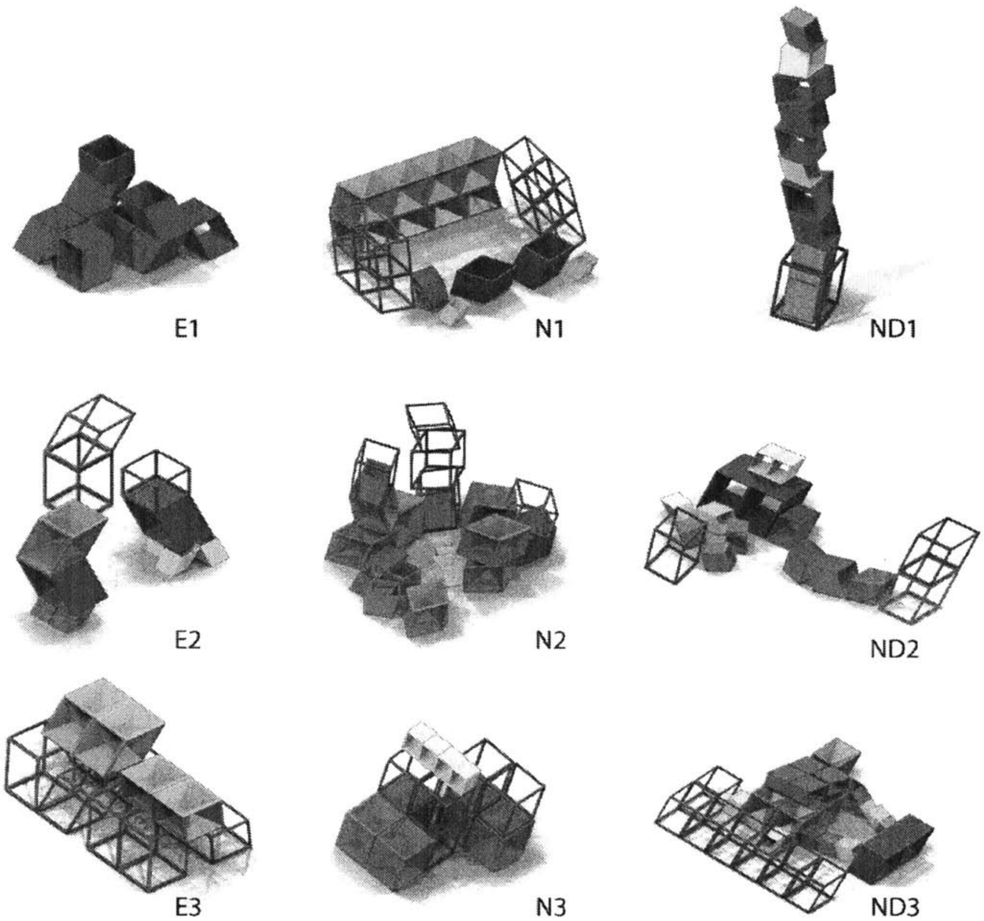


Figure 5.10 Nine dream house designs by experienced architects (left column), novice design students (middle column) and non-design students (right column).

5.3.3 Formal composition

Lastly, the architects' dream house designs have a sense of order and formal composition that is missing from the novice and non-design student models. Some novices and non-designers' designs had more loosely organized relationships between the blocks than did the experts' designs. This is especially the case with N1, N2, ND1, ND2, and ND3 in comparison to E1-E3. The novice and non-designer models appear more chaotic and random in their block arrangements compared with the experts' designs which appear to have more strict alignments.

5.4 Coding the Interaction Results

My framework provides a vocabulary to discuss model making and material interaction as a pick and place activity in measurable terms of body movements and body-material interactions. It is a descriptive framework only however and I do not claim the actions are necessarily intentional or causal. With my small sample size, my findings are qualitative and tend to be anecdotal. However, they are revealing of certain behaviors that I think can be called designerly.

The central question I explore in analyzing the results is: can the differences observed in the verbal protocols and design models be reflected in the physical interactions exhibited by the different participants groups? Is a particular interaction such as Modifying block relationships or Assembling blocks together found more or less in the architects when compared to the other two groups? Is there a kind of designerly material interaction? My hypothesis stated that I would indeed observe different behaviors across the groups and that these behaviors, the physical interactions with the blocks, would lead to more designerly thinking.

To find this I look for interaction patterns in the sequences of behavior that distinguish the architects from the novices and non-design students. Each participants' session was broken down by the coding scheme described in Chapter 4. However, it is important to note that with my small sample size, there are cases with extreme outliers in the data set that may throw off group averages and make comparisons inaccurate or misleading. Where I can I look for trends that show a progression of behavior from the experts, to the novices, to the non-designers. For example, would we see that Adding actions are found highest non-designers' protocols and lowest in the Experts'?

5.4.1 Analyzing primitive interactions

I first coded each of the subject's video sessions in terms of primitive interaction types: Add, Subtract, Modify, and Relocate. I did not count at the level of pick or place movements or individual block transformations such as a rotation or translation in a particular axis. I counted Add, Subtract, and Relocate actions in terms of instances with individual blocks. For Modify interactions, I counted both in terms of instances and the duration of time spent in transformation. Additionally, I counted the special case of Inspect-actions for each interaction in terms of instance and duration of time. For example, in Table 5.2 below, subject SK did 26 Add actions. This accounted for 23.4% of all of his primitive interactions. Of the 26 Add actions, 4 were Add-inspect interactions. Accordingly, table 5.2 shows the general coding results for the four primitive interaction types and their special case inspect-actions for each of the participants.

I count Add interactions as those where the subject picks up a block from the site and places it on or near the configuration. Subtract interactions are in the reverse: the subject picks up a block from the configuration and places it on the site. Modify interactions are counted when the participant picks up a block from the configuration and places it back in the configuration. Relocate interactions are counted when a participant picks up a block from the site and places it back on the site either in the same or different location.

With these four interaction types I can total the number of interactions for each subject and for each group. Total interactions counts for the nine participants range from 45 to 162 interactions (See Table 5.2). This total includes interactions and inspect-interactions. These counts vary across and within each group of subjects and depend largely on the amount of time spent in the task. In Figure 5.11 I show the mean number of interactions for each type per participant group.

I did a Chi-Square analysis to test the null hypothesis that the physical action data represent a chance distribution. The result is $x^2(6, n=9) = 32.22$ $p < .01$. This is a very low probability and we can therefore confidently reject the null hypothesis and claim there is a significant relationship between participant group and interaction count. But what is the relationship?

5.4.2 Interaction time

For Add, Subtract and Relocate interactions I counted each action instance as a nominal one second of duration. In other words, one action equals one second. This was accurate in terms of what I observed as the typical amount of time spent in completing these actions as this was about how long it took to translate a block from one location to another on the site. Some actions took less than a second. For Modify interactions I counted the actual duration time. This is because I wanted capture the trend that more manipulation was involved besides just translating a block across the site. For example, a participant may spend time Modifying the block by rotating it on or near the configuration to better understand its shape.

I counted the time for Inspect-interactions separately from the regular interactions. These actions typically took longer than one second as the participant would spend more time in

Table 5.2 Interaction counts per subject with aggregate totals and times

Interaction Type	Architects			Novices			Non-designers		
	RM	SK	BC	MR	JG	JC	CY	FT	RW
# of ADD Actions	11	26	16	42	36	26	21	23	33
% of Total	24.4	23.4	28.1	28.6	22.2	24.3	39.6	25.0	31.1
Add-inspect	0	4	1	0	1	0	2	1	11
time/action	1.0	1.0	1.0	1	1.1	1	1.2	1.1	2.5
# of SUBTRACT Actions	5	12	4	9	13	9	6	5	7
% of Total	11.1	10.8	7.0	6.1	8.0	8.4	11.3	5.4	6.6
Subtract-inspect	0	0	0	1	2	0	0	0	0
time/action	1.0	1.0	1.0	1.0	1.5	1	1	1	1
# of MODIFY Actions	19	41	20	59	90	35	13	29	17
% of Total	42.2	36.9	35.1	40.1	55.6	32.7	24.5	31.5	16.0
Modify-inspect	0	0	0	1	5	4	2	0	1
time/action	5.5	6.6	3.5	5.0	2.6	4.5	4.9	4.2	2.8
# of RELOCATE Actions	10	32	17	37	23	37	13	35	49
% of Total	22.2	28.8	29.8	25.2	14.2	34.6	24.5	38.0	46.2
Relocate-inspect	2	15	4	20	9	8	12	26	22
time/action	1.1	3.5	1.4	1.9	2.0	1.4	2.4	4.7	1.8
Total Action Time	130	410	113	429	340	243	126	335	227
Total Actions	45	111	57	147	162	107	53	92	106
Block count	9	12	12	22	15	22	12	16	29
Actions per block	5.0	9.3	4.8	6.7	10.8	4.9	4.4	5.8	3.7
Time per block	14.6	34.2	9.4	19.5	22.7	11.0	10.5	20.9	7.8

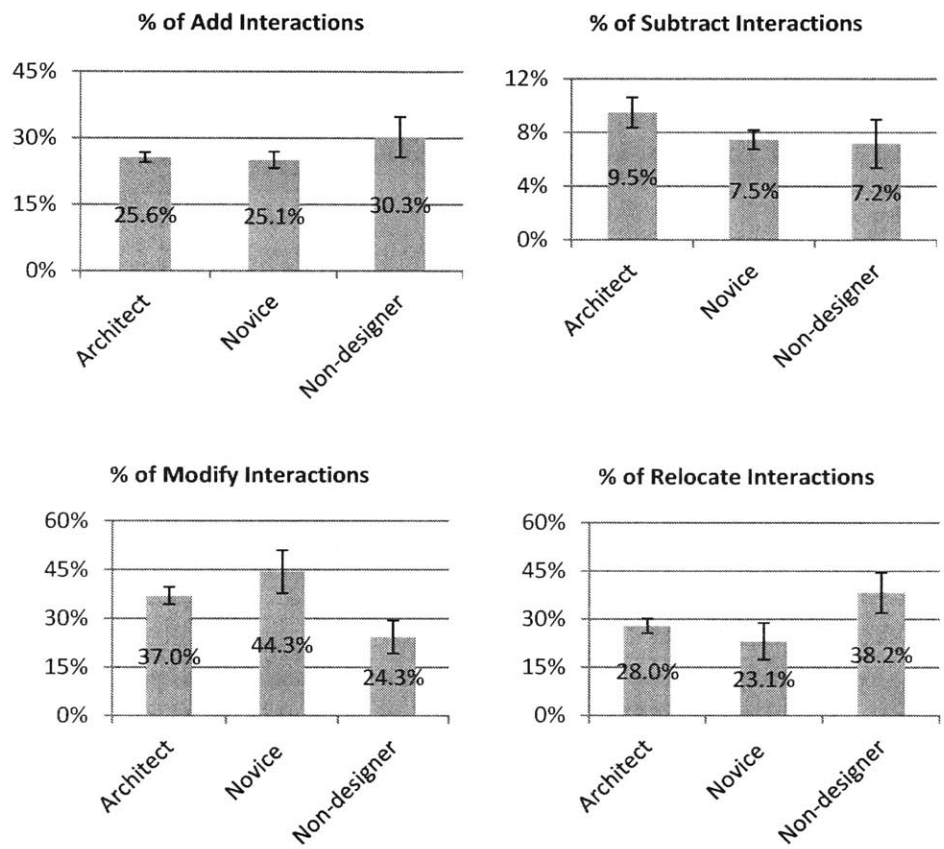


Figure 5.11 Mean percentages of primitive interaction types per participant group with standard errors shown.

bringing the block closer to their face to have a closer look. For example, participant FT on one occasion spent 16 seconds inspecting a block during a Relocate-inspect interaction.

I added the time for all inspect-actions and all regular interactions for each participant to generate a Total Action Time for each participant, as shown at the bottom of Table 5.2. These action times range from 113 to 429 seconds. These figures do not account for time spent not in action. Some subjects spent much of the time not moving or interacting with the blocks. In some cases non action was significant and may have shaped the design, however, I did not calculate this time as it may have represented a period when the participant was talking about his design process with the researcher.

5.4.3 Interaction Rates

I considered the final count of blocks in the each participant's final configuration in relation to the amount of total time spent interacting and the total number of interactions to derive figures for time spent per block and the number of actions per block. There is a descending trend in time spent per block based on participant group from architects to novices to non-design students (See Figure 5.12). However there is significant overlap in the error bars, suggesting that a larger study would be need to confirm any suggestions.

Furthermore, there were large differences within each of the groups. For example, as seen in Table 5.2, subjects SK and BC, two architects, had respective block interaction rates of 34.2, (the highest of all the participants), and 9.4 sec/block (the lowest). What accounts for this difference? What does SK achieve by spending more time interacting with each block? In his design participant BC made an historical reference by using the wire-frame blocks as a *pilotis* to lift his house off the ground. Perhaps once he made this reference he did not need to interact with the blocks as much, whereas SK continually shaped his design through exploring potential relationships between the blocks.

5.4.4 Add Interactions

All three participant groups were closely related in regards to their percentages of Add interactions with a 17.4 point spread across the groups. Add actions include any movement where the subject picks up a block from the site, translates it across space and places it on or near the configuration. Add actions require that there be a configuration already in place, thus the first action cannot be an Add action.

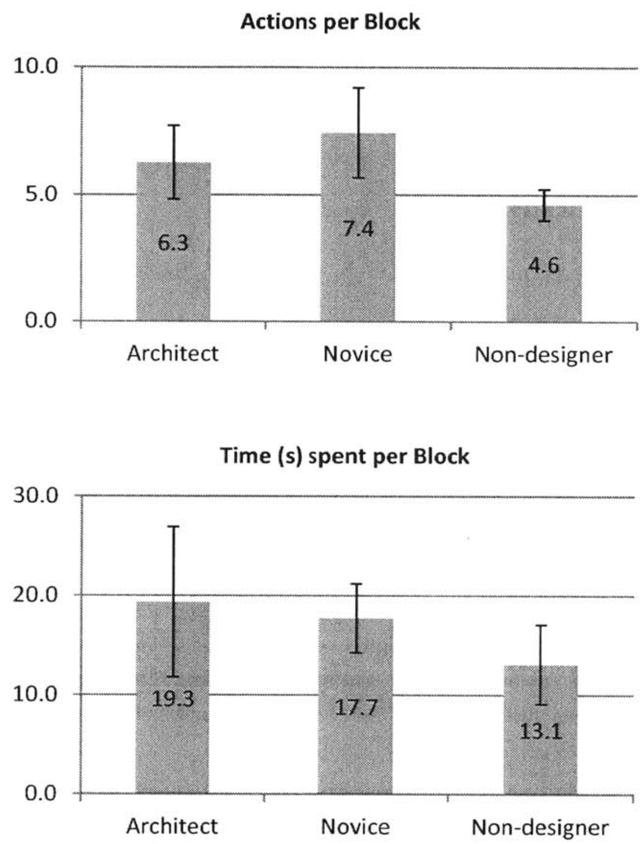


Figure 5.12 Mean interaction rates per participant group with error bars

Subject CY, a non-design student had the highest percentage of Add interactions, 39.6%, over 12 points higher than the mean for all the participants in the study which was 27.5%. Why is this participant's count so much higher? Does this say anything about her interactions with the blocks as a non-designer? Higher Add interaction percentages are frequently coupled with lower Modify action percentages. I found that the two participants with the highest counts for Add interactions also had the lowest count for Modify interactions.

Is there a decision made to either Add or Modify a block? CY built her dream house as a rock climbing gym (Figure 5.10, ND1). She added the blocks one on top of another to create different rooms which one would climb up to get to the next level. Her design was very conducive to Adding actions. She likely would have had even more add actions unless her design became physically unstable and unable to support any more blocks. On the other hand, subject JG had the fewest Add actions, 22.2% and the greatest percentage of Modify actions.

5.4.4.1 Add-Inspect Actions

These actions are defined by movements where the subject does an add action but introduces additional transformations bringing the block closer to his or her face as s/he translates the block towards the configuration. I found that this was the third most common type of block inspection after Modify-inspect and relocate-inspect. By looking more closely at the block as they added it to a configuration, the participant was gaining additional information about the block. The inspection could also be used as a filter to determine if the block should be added to the configuration. Another use of the inspection could be in helping determine in advance what orientation the block needs to be in to be placed in the configuration. Some of the participants would build configurations with blocks all in the same orientation, e.g., N3 and ND3 in Figure 5.10.

On average all the participants spent the second least amount of time per action doing Add and Add-inspect actions, spending only 1.2 seconds/action. Participant RW spent the most time per action, with 2.5 seconds per action. In two instances he spent over 10 seconds inspecting a block before he added it to the configuration.

5.4.5 Subtract interactions

Subtract interactions include any movements where the subject picks a block from the configuration, translates it across space and places it on the site away from the configuration. Across all three groups the mean percentage of Subtract interactions was 8.1% of the total. These were the least common interaction for all participants. Subject CY had the highest percentage at 11.3%. Noting that this participant also had the highest percentage of Add actions and only 12 blocks in her final design, it would seem that these two types of interactions balanced each other out. Subtract interactions also accounted for the lowest range across all the participants, with only a 5.9 point spread. A question to consider is: why does a block need to be removed? Can it not be repurposed? When participants subtracted blocks from the configuration, it would seem that they were typically finished with considering that block and that no further inspection was required. However, it is possible that an inspection of the block changed the Subtract interaction into a Modify interaction.

5.4.5.1 Subtract-Inspect

I rarely observed this kind of inspection action. Only two novice participants, JG and MR, did this kind of inspection action. The average time for all subjects was 1.1 seconds/action.

5.4.6 Modify interactions

This kind of interaction was the most common in the dream house design task. Modify interactions include movements where the participants picks up a block from the configuration, manipulates the block and then places it back in the configuration. It may result in a block being in the same location and orientation or different ones. What is key about this kind of interaction is that it results in no additional blocks added to the configuration, however additional information may be uncovered.

All participants except CY and RW (two non-designers) spent the majority of their time Modifying blocks in a configuration. The mean percentage of Modify interactions for all participants was 35.2%. Participants JG, a novice designer, had the highest percentage at 55.6%. She had the lowest percentage of Add and Relocate actions. This means she was manipulating blocks already in her configuration instead of adding more blocks to it. Interestingly, even though she had the highest percentage of Modify actions, she also spent the least amount of time per action, only 2.6 seconds per Modify interaction. Her modify actions, as was apparent in the video recordings can be characterized as incremental: she made many quick Modify interactions. The second highest percentage count was subject RM, an architect, who had 43.2% of his interactions as Modify interactions. Participant SK, an architect, spent 6.6 seconds per Modify action, the most amount of time of all participants in the study.

RW, a non-designer, had the lowest percentage of Modify interactions. Only 16% of his actions were Modify actions. How can his approach to working with the blocks be characterized in contrast to the others? He also used the second highest number of blocks at 29 blocks in his model. His approach, as he articulated it, seemed less about developing a design concept and more towards finding certain blocks to represent certain rooms.

Overall, I did not find any trends progressing from the experts to the non-designers (see Figure 5.11). The novice designers had the highest percentage of modify actions at 42.9%. The experts were 37.9% and the non-designers were at 24.8%. I did expect that the experts would have the highest percentage of Modify actions. I think this result suggests that while modify interactions are important, there may be other aspects of interaction that need to be considered to make claims about what designerly interaction is. Furthermore, I think larger scale studies would help reveal more significant differences.

5.4.6.1 Modify-Inspect

These kinds of interactions were also limited compared to the other types of inspection actions. It seems that the Modify interaction on its own already produces enough block manipulation and exposes enough information to help the participant determine the resulting position of the block in the configuration.

5.4.7 Relocate Interactions

Relocate interactions include movements where the participant picks a block from the site, translates it across space and places it at the same or different location on the site, away from the configuration. Compared to the other interactions, this was the second most common across all of the participants. Two non-design students spent the majority of their time relocating blocks. FT had 37% and RW had 46.2% of relocating actions. Why did they spend so much interaction moving the blocks around on the site away from any configuration? Conversely, only 14.2% of JG's (a novice) interactions were Relocate actions. Perhaps Relocate interactions can be likened to doodling activity in sketching, where one isn't really performing a specific action to reach a goal, but rather moving around to possibly stir up ideas.

5.4.7.1 Relocate-Inspect

This kind of action was the most common kind of inspect interaction. This is when a subject picks up a block from the site, looks at it while manipulating it close to his face or on the surface of the site, and places it back down on the site. As a mean percentage of all Relocate actions, Relocate-inspect actions were 36.7% for all subjects. I did observe a clear trend across the groups (See Figure 5.13). The architects tend to inspect the blocks the least, 30.1%, the novices 35.2%, and the non-designers 44.7%, as a percentage of their total relocate interactions.

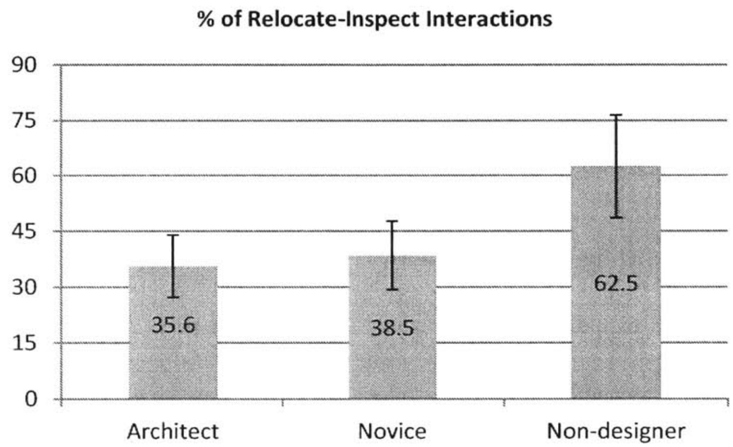


Figure 5.13 As a percentage of their total Inspect interactions, architects and novices perform much fewer Inspection interactions than the non-designers.

5.4.8 Discussion of the primitive interactions

Only a few trends can be observed ranging from the architects to the novices to the non-design students, for example in the percentage of Subtract interactions (Figure 5.11) and time spent per block (Figure 5.12). The standard errors for these results do not indicate clear distinctions. However, some interesting observations can be made by comparing two groups to the third, for example comparing how both architects and novices are similar to each other and can be contrasted to the novices, or how architects differ from the two other groups. Importantly, there is never a condition where architects are more similar to the non-designers than to the novices. This result helps validate the coding scheme's value in shedding light on what designerly interaction looks like.

Looking at the Add interactions per participant group in Figure 5.11, one can see that the architects and novices are more similar than are the novices and non-design students. Instead of constantly adding more and more blocks to a configuration, the architects and novices seem to get more out of fewer blocks. Why is it that the architects and the novice design students are similar in this regard? Examining the results in Modify and Relocate interactions we similarly find that the architects and novices are more similar when compared to the non-design students. What is it about performing Relocate and Add interactions less, and performing Modify interactions more that distinguish both the architects and the novices from the non-designers? Furthermore, we found that architects and novices spend more time and more interactions per block than the non-design students. Together these results can be characterized in terms of the designerly notion of doing more with less. Importantly this work provides a link between specific kinds of interactions in designerly doing.

On the other hand, looking at the Subtract interactions we find that the novices and the non-design students are more similar (Figure 5.11). The architects would appear to be more selective and willing to remove material as the design idea evolves. Is this a skill that needs to be learned by the novices? How do they become more like the architects in this regard?

However, many questions do arise from this simple analytical framework. Some of the largest differences in interactions were found within the groups, especially within the novices and non-designers. Figure 5.14 shows the percentage of interaction types for each participant across all three groups. For example, with Modify interactions the non-designers range from 16.0% to 33.7%, and their Add interactions range from 23.9% to 39.6%. The novices have wide ranges of interactions as well. For Modify actions the novices range from 33.0% to 55.6% and for Relocate interactions they range from 14.2% to 34.0%. The experts tend to be the most self-similar, having the tightest grouping across their interactions. This could be reflecting the fact of training: the experts have similar training and practices whereas the novices and non-designers have backgrounds which are more varied and have had little to no training.

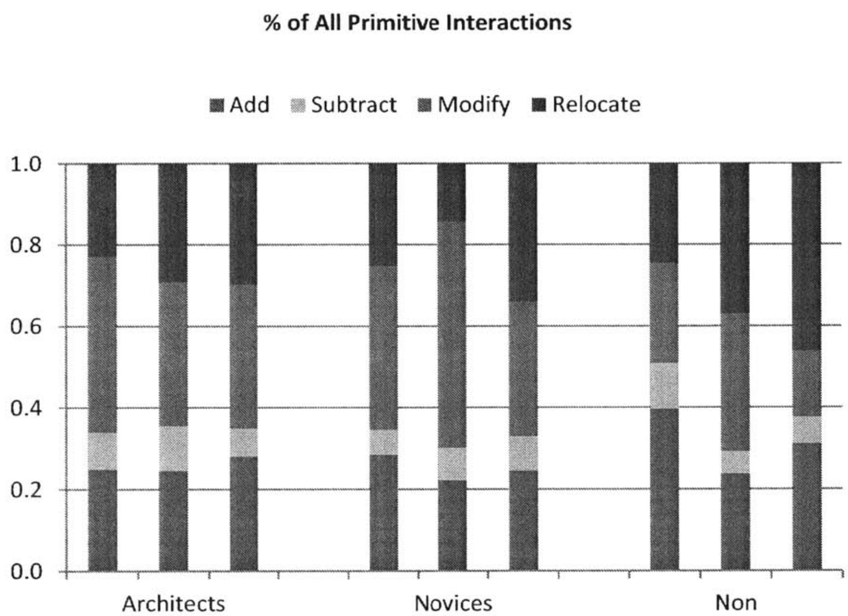


Figure 5.14 Percentage of primitive interaction types for each subject.

As noted above, however, the Relocate-inspect action shows trends across the three subject groups. Why do the experts tend to inspect the individual block less? We speculate that it is more designerly to work with the blocks in groups of blocks, in the configuration, as opposed to blocks in isolation. For the experts, perhaps the meaning of the blocks is to be found more in the relationships between them than in a singular block.

5.5 Analyzing Interaction Sequences

Looking at the primitive interactions as isolated actions only conveys part of the story. It is also important to consider how interactions are related to each other over time. By grouping interactions together I provide a structure for speculating on the intention and goals of interactions. With this we can consider in what context the interactions occur. Are there different stages of interaction? Are there patterns between interactions? Do certain interactions group together more often than others? Figure 4.5 from Chapter 4 provides an example of the interaction sequences and verbal protocol. Interactions are listed out individually with the time that they occurred. If an interaction had duration of greater than 1 second the amount of time was indicated next the interaction. Interactions sequences including Assemble, Explore, Manage, Disassemble, Test:Eject, Test:Accept, and Test:Reject are indicated by color coding. Simultaneous interactions (two-handed interactions) are indicated with a slash mark, e.g., if a participant uses two hands to relocate a block, this is indicated as Relocate/Relocate. Also included are the participant's verbal accounts made during the design session. See Table 5.3 for interaction sequences for each participant.

There are three general types of interaction sequences that I observed: Consecutive, Compound and Coordinated. Consecutive interactions involve three or more identical actions in a row. There are four types of Consecutive interactions. For example, Add-Add-Add interactions I count as one kind of consecutive interaction. Compound interactions occur when the place location of one action becomes the pick location of next action. For example, when a participant Adds a block to a configuration and without putting it down, does a Modify action, this I considered a Compound interaction. There are three types of Compound interactions. Coordinated interaction sequences are two-handed interactions. There are two types: synchronous and asynchronous. For example a subject may modify a block using both hands. This would be a synchronous interaction using two hands to do the same interaction. Asynchronous interaction is doing two different interactions with two hands. See Table 4.4 in Chapter 4 for interaction sequence definitions. I also speculate that other kinds of interaction such as alternating interactions could exist. However, my analysis did not account for this kind.

Table 5.3 Interaction sequence counts and percentages for each participant.

Interaction Type		Architects			Novices			Non-designers		
		RM	SK	BC	MR	JG	JC	CY	FT	RW
Consecutive Interactions	Manage	1	3	2	6	2	5	1	4	4
		8.3%	11.1%	21.4%	17.6%	6.3%	22.7%	11.1%	21.1%	23.5%
	Assemble	0	0	1	1	0	1	1	1	4
		0.0%	0.0%	7.1%	2.9%	0.0%	4.5%	11.1%	0.0%	23.5%
	Disassemble	0	0	0	0	0	0	0	0	0
		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Explore	1	2	2	2	6	0	0	1	0
		8.3%	7.4%	14.3%	5.9%	18.8%	0.0%	0.0%	15.8%	0.0%
Compound Interactions	Test:Reject	2	5	1	2	5	3	1	1	1
		8.3%	18.5%	7.1%	5.9%	15.6%	13.6%	11.1%	5.3%	5.9%
	Test:Accept	6	13	7	22	17	11	5	11	7
		50.0%	48.1%	50.0%	64.7%	53.1%	50.0%	55.6%	57.9%	41.2%
	Test:Eject	3	4	1	1	2	2	1	0	1
		25.0%	14.8%	7.1%	2.9%	6.3%	9.1%	11.1%	0.0%	5.9%
Coordinated Interactions		1	9	4	14	38	11	8	7	8
Total Action Time		115	398	93	429	340	243	126	335	227
Total Interactions		13	27	14	34	32	22	9	18	17
Interactions per minute		6.3	4.1	9.0	4.8	5.6	5.4	4.3	3.4	4.5
Interactions / Actions		54.5%	58.2%	59.6%	53.7%	48.8%	50.0%	39.6%	50.0%	41.5%

I first counted individual instances of interaction sequences and then I totaled the interactions. For example, participant RM, an architect, had 1 Manage interaction, 1 Explore interaction, 2 Test:Reject interactions, 6 Test:Accept interactions, 3 Test:Eject, and 1 simultaneous interaction. I then totaled the number of interactions by adding only Consecutive and Compound Interactions. I consider Coordinated interactions to be a different class of interaction and therefore do not include it in this total. By considering the percentage of a particular interaction in relation to the total number of interactions I can compare individual participants with one another. For example, only 8.3% of RM's total interactions were of the type Manage, whereas RW's (a non-designer) percentage was 23.5%.

5.5.1 Consecutive interaction types

There are four kinds of Consecutive Interactions: Manage, Assemble, Disassemble and Explore. It is within these interaction types that I find the most consistent trends progressing from the architects to non-designers (See charts in Figure 5.15). Architects had the lowest percentage of Manage interactions at 11.1%, although the lowest for all participants was JG, a novice designer at 6.1%. On average, non-designers had 18.6% Manage interactions. Most notably, the architects exhibited only 1.9% Assemble interactions where novices had 2.2%, and non-designers had 13.6%. Lastly, the architects had the most Explore interactions at 9.3%, where non-designers had only 2.3%. It can also be noted that overall the architects tended to have the least amount of total Consecutive Interactions compared to novices and non-designers.

5.5.1.1 Manage interaction sequences

I identified Manage interactions as groups of Relocate-Relocate-Relocate interactions. Overall, compared to the other interaction sequence types, participants spent the least amount of time managing the workspace. I observed three kinds of examples of Manage interactions on the site: pre-sorting blocks, clearing space for future expansion of a configuration, and shuffling blocks around. Some of the participants organized the blocks at the beginning of the session (Figure 5.16). Subjects MR and RW spent a significant amount of time sorting the blocks at the beginning of the session. Organizing the blocks as such from the outset may help establish what and how much material is available but it may also reinforce preconceived ideas as to what the blocks represent. As seen in Figure 5.15, there is a progression from the architects to the novice designers to the non-designers. This result suggests that the architects pay less attention to blocks on an individual basis and also on grouping similar blocks.

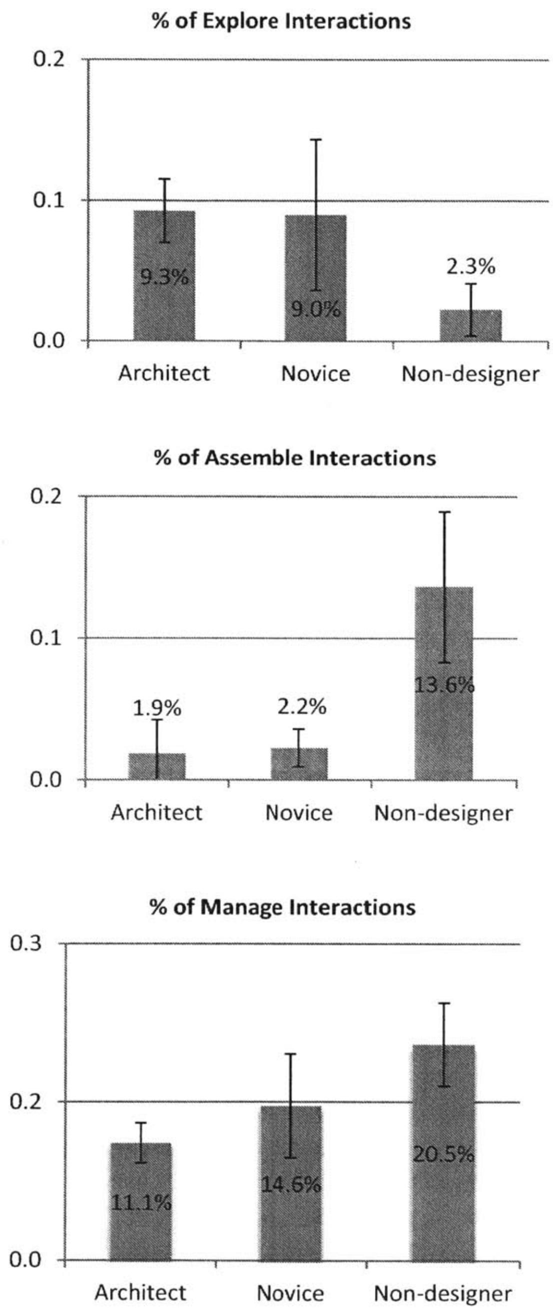


Figure 5.15 Mean count for Consecutive interactions by percentage of the total for each subject group with standard error bars.

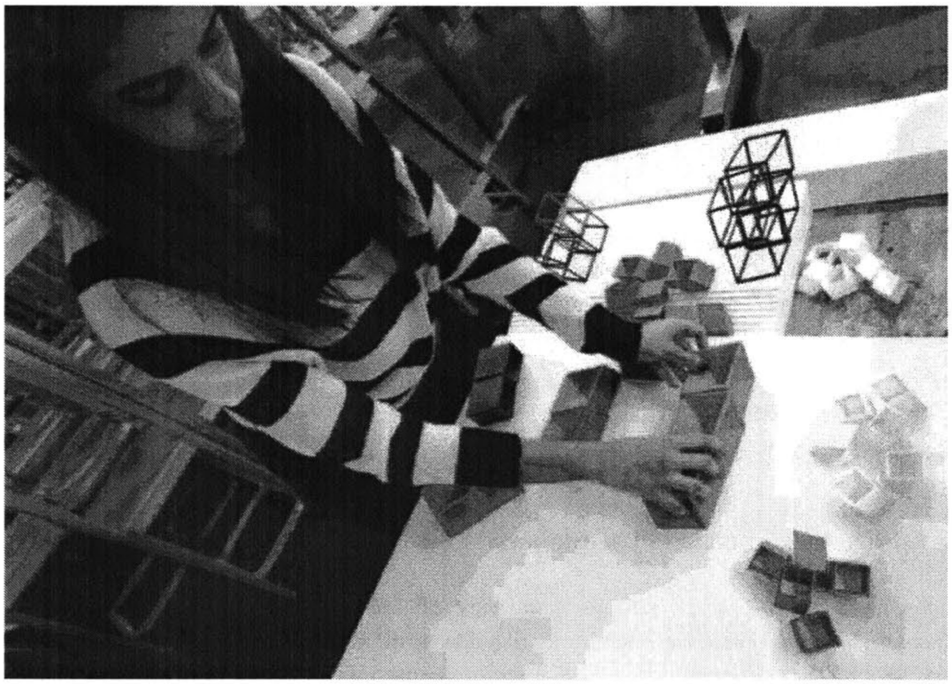


Figure 5.16 Subject MR, a novice, managing the workspace by organizing blocks into like colors and shapes.

5.5.1.2 Assembly interaction sequences

Assembly interaction sequences include groups of Add-Add-Add interactions. Overall, very few Assembly interactions were observed, however the non-designers did exhibit some of this behavior (See Figure 5.15). In this kind of interaction sequence no modification is made to the blocks as they are brought to the configuration other than translation. Subject RW exhibited 4 distinct instances of assembly interactions (Table 5.3). After one instance of this interaction sequence he explained the idea that he created with the blocks: "it'd be cool to have a wall of windows along the side of the house." He repeatedly added duplicates of the same block to create his window wall. Apparently, no Modify interaction was needed to further align the blocks. Assembly interactions would indicate that the design idea is thought of in advance and involves no Modification.

In the case of Assembly interactions I find the architects and novices to be the very similar. Does this suggest that there is an inherent way of interacting with blocks as a material that can be said to be designerly? Why do the non-designers perform this kind of sequence over 6X as much? When working with physical material in discrete units it seems that the designers (both architects and novices) work with the smallest unit available, the block's orientation) and the design idea can change depending on this orientation. In other words, the modification of each block represents an opportunity to exploit.

5.5.1.4 Explore interaction sequences

Explore interactions are defined as sequences of Modify-Modify-Modify interactions. Although in general infrequent, here too I find a trend from architects to non-designers (see Figure 5.15). The architects and novices show a similar rate of Explore interactions, much more so than the non-designers. This finding reinforces the lack of Assembly interactions in the architects' and novices' protocols and seems to be the inverse. With more frequency, each block holds an opportunity for exploring its potential orientation. I characterize Explore interactions as opportunistic behavior.

However there is great variance within the groups especially the novices and non-designers, ranging from 0 to 18.2% in the novices. JG had the highest percentage of Explore interactions. In recounting from her verbal protocol, JG set a design goal of connecting two spaces on the site. In working towards this goal she commented,

> "I realized especially when I dealing with shapes I'm not familiar with...if something's in 2D I can imagine it in my mind...but if its 3D I don't know what kind of problems I'm going to have so I feel like I can't prepare for it...I just have to do it."

Consecutive Modify interactions where you manipulate blocks at the configuration are perhaps a way of 'just doing it' without preparing for it. The blocks are indeed difficult to predict and so one may start with an idea based on a particular vantage point and block orientation, but through manipulation end up having a different problem to solve.

5.5.1.3 Disassembly interaction sequences

I did not observe any disassembly interactions during the design task. Participants did subtract blocks from configurations occasionally however never three of these interactions consecutively. It is perhaps easier to represent ideas of one's dream house with the blocks as opposed to the absence of blocks. Additionally, very few participants explored the idea of creating negative space by adding blocks together and strategically subtracting them.

5.5.2 Compound interaction types

Compound interaction types are defined when one interaction is merged with another so that the place location of the first interaction is the same as the pick location of the second interaction. There are three kinds of Compound interactions: Test:Reject, Test:Accept, and Test:Eject. All Compound interaction types contain a Modify interaction coupled with and Add and/or Subtract action. For example, a participant may Add a block to the configuration and without pausing begin to Modify that same block within the configuration. This would be a Test:Accept Compound interaction type. I consider these interactions to be tests where a new condition such as a new block or a new block orientation is considered. It is important to note that the final decision is not necessarily known in advance of starting the interaction. For example a Test:Eject interaction may begin as a Modify action, however through manipulation it is determined that the block should be removed.

5.5.2.1 Test:Reject interaction sequences

A Test:Reject interaction sequence is characterized as a negative test that leaves the configuration in the same state as it was before the interaction. It is composed of the following sequence: Add-Modify-Subtract. In this case, a participant tests a block by Adding it to and Modifying it near the configuration, however an acceptable position could not be identified so it is Subtracted. The configuration remains the same. This happens all as one fluid motion combining the three actions into one.

There is a descending trend from the architects to the non-designers with this interaction type (See chart in Figure 5.17). Architects had the highest mean count, 14.8% of their interaction sequences were Test:Reject. Expert participant, SK, had the highest percentage out of all participants, at 18.5%. On two occasions he commented either during and right after doing so about what he was looking for:

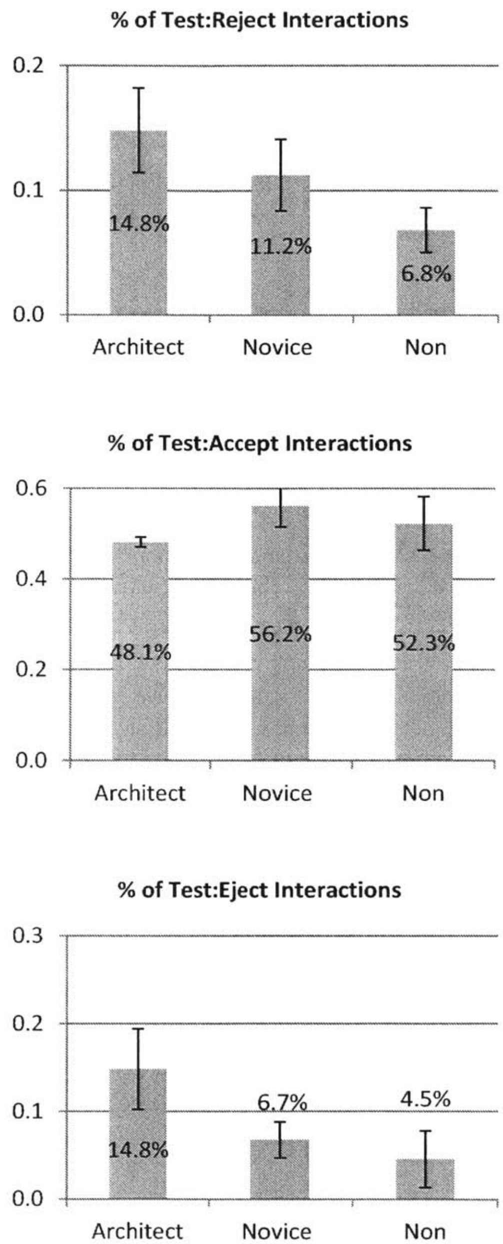


Figure 5.17 The three Compound interaction sequences per participant group with standard error bars

"I would normally do a skip thing…2 up 1 down…but there's no green [block]."

He was seeing a potential pattern – '2 up 1 down' – with the blocks but he could not find a particular block to complete the pattern so he Rejected that particular block. At a second time after a Test-Reject interaction he said:

"That would have been cool…that's a shame…what would have been apex to apex."

In this example he was hoping that a particular relationship would exist between two blocks – 'apex to apex' – and by manipulating the block he discovered it was not possible (Figure 5.18) so he rejected the block.

Why do the architects have a higher percentage of this kind of interaction type and what might explain the descending trend? Characterizing this interaction sequence as a negative experiment suggests that the architects perhaps set up more particular manipulation experiments. While architects may be opportunistic in how they Explore with the blocks, they also set out with specific criteria by which to decide to either keep a block or not include it in the configuration.

5.5.2.2 Test:Accept interaction sequences

This is the most common interaction sequence I observed—across all participants, 52% of all interactions were Test:Accept interactions. See Figure 5.17 for a breakdown per participant group. Given that the task was to construct a model with blocks it makes sense that these kinds interactions were most common. In these interactions subjects Add a block to their configuration, Modify it, and then leave it in the configuration. The configuration increases in the number of blocks it has. Comparing this to the Assembly interaction sequences which was only 4% of all interactions, I confirm that working with a physical material requires a high degree modification and not just addition.

There is a significant range across all the subjects, from 41.2% to 64.7%. Test:Accept interactions were often grouped together where a subject would repeatedly do Add-Modify actions. On one occasion subject MR (64.7% of her interaction sequences were Test:Accept) was building a wall out of the blue blocks. Three times in a row she picked up a blue block and modified it near the configuration and placed it there. It is clear she has an orientation in mind to along which to align the blocks, however she modified each block after adding it to the configuration.

Interestingly, the architects had the fewest Test:Accept interaction sequences. This finding aligns with their higher rate of Test:Reject sequences and further reinforces the idea that architects may be setting up more critical experiments to determine whether or not to keep a block in the configuration.

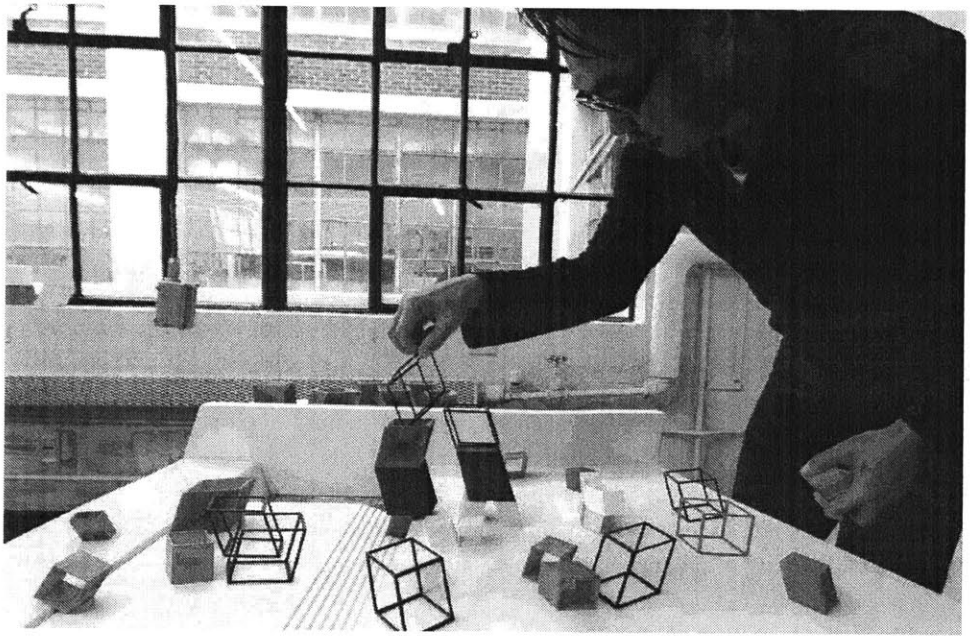


Figure 5.18 Participant SK, an architect, testing the relationship between blocks. This was a Test:Reject interaction type.

5.5.2.3 Test:Eject interaction sequences

Of the three Compound interaction sequences, Test:Eject was the least common across all subjects. This is distinguished from Test-Reject interaction sequences in that the block that is picked starts out in the configuration and is removed. The configuration decreases in the number of blocks. With these interaction sequences I find a trend across the subject groups where the architects are at 14.8%, novices at 6.7%, and non-designers are at 4.5%. Ejecting a block can make room for other blocks or can reveal relationships between the other blocks. Architect participant RM had the highest percentage of Test:Eject sequences at 25.0%. RM also had the fewest number of blocks in his final configuration.

Similar to the results of Test:Reject, there is a descending trend from the architects to the non-designers. Why do architects do this more frequently? What is it about removing a block from the configuration that architects are doing?

5.5.3 Coordinated interaction types

I counted Coordinated interactions separately from compound and consecutive interactions; I did not include them in the total percentage. Coordinated interactions are when the subject does an action(s) with both hands at the same time. By framing actions and interactions as such I am more concerned with the manner in which an action is carried out than with what action is carried out. These ranged widely from 1 instance to 38 instances. In nearly all instances the interaction type was the same for each hand, for example Modify/Modify or Add/Add. It was also common for the subject to hold a block in one hand while manipulating another block in the other hand. However, in my analysis we did not distinguish between synchronous and asynchronous interactions.

5.5.4 No Action

I found that with many of the participants a large amount of time was spent not interacting with the blocks. In some cases the participants would pause and stare at their configuration for long periods. It was also common that when the participants were talking about their designs that they would not be manipulating any blocks. Much of the time not interacting with the blocks was spent in moving themselves around the site model. This was especially true for the architects. This may indicate that body movement on its own has implications for the design process, such as gaining new perspectives or zooming in close to see particular views.

5.6 Design thinking in Pick and Place Activity

Over the course of this project I observed many kinds of body-material interactions with the blocks. I gave these interactions particular names: assembling, disassembling, managing, exploring, rejecting, accepting, and ejecting, along with coordinated interactions. I observed four kinds of primitive interactions which serve as the basic unit of material interaction: adding, subtracting, modifying, and relocating. Together these terms shape how one can examine and describe what it means to think with a body in a designerly way. This framework shows that even though we are quite limited in what we can do physically with blocks, we can achieve great variety and complexity by engaging the body with material.

Although the sample size of this study was small (n=9) there is ample evidence in the interaction analysis presented to claim that there are indeed designerly ways of exploratory model making. Exploratory model making can be described in terms of body-interaction. One of my goals was to distinguish between the three subject groups by their physical actions. I hoped to see trends from the experts to the novices to the non-designers. After all, if there is a *physical* design intelligence, then it should be lacking in non-designers, showing slightly in novice designers and present to larger degree in the architects.

Questions we can discuss include: is one particular interaction more designerly than another? Evidence for this rests in the differences in the architects' behaviors and the novice and non-designers. Is it more designerly to modify blocks as opposed to adding them or relocating them? What about exploratory interactions vs assembly interactions—does doing these signify designerly behavior?

5.6.1 Related work

Many previous studies have analyzed the design process through protocol analysis with different research goals and different design tasks and mediums but do so by comparing novices and experts. Suwa and Tversky (1997) explore how architects perceptually interact with their sketches. They argue that the "design process [is] composed of cycles of focus shifts and continuing thoughts…each small cycle is driven by designers' actions of seeing different information categories." Their study included 7 students and 2 architects. They found significant differences between the number of 'dependency chunks' in the two groups, meaning the architects think longer and deeper about a particular topic. Suwa Purcell and Gero (2000) conduct a protocol analysis study on a single architect to better understand how designers invent new problems on the fly in sketching activity, what they call situated-invention. Kavakli and Gero (2002) do a protocol analysis on a novice and expert designer to explore the structure of design thinking finding that experts have more hierarchy and simultaneous connections between six cognitive actions: drawing, looking, perceptual, functional, goals, and moves. Bilda and Demirkan (2003) studied six interior designers to understand the differences in digital vs. sketching mediums.

My study can be distinguished along three lines. First, I look at three groups and attempt to identify trends in actions from experts to novices to non-designers. Such trends will indicate certain learned behaviors. Secondly, with my framework I focus exclusively on physical action. Other studies generalize physical action into drawing and/or looking actions. Lastly, I study a design activity that is not sketching. Most studies explore sketching either on its own or in comparison to digital media. My study focuses on model making in terms of pick and place actions with blocks.

5.6.2 Structured vs non-structured interactions

Overall, one of the clearest trends I observed in the study was with the structured nature of the interactions. I found that architects' interactions on average were structured as Compound or Consecutive types at a higher percentage than novices and non-designers (See Figure 5.19). Experts had a mean interaction percentage of 60.7%, novices 50.8%, and non-designers 42.6%. What this suggests is that architects work with the same block for longer periods of time performing more interactions on them before moving on to other blocks.

5.7 Chapter Summary

Designerly interaction is based on exploratory manipulations which exploit material properties and spatial relationships. In this study exploratory action is defined as modifying material within a configuration of blocks—either rotating or translating the blocks. This is contrasted with Adding more material or Relocating material outside of the configuration. In my study I found that architects and novices more frequently explored with the material than the non-designers. What does this say about the similarity between architects and novice designers? Perhaps this kind of action in inherent to those with design-focused predilections. Designing with physical material—blocks—is more than assembling them together as if the idea just needs to be made physical Rather, design ideas are formed through the interaction with the material and exploits their affordances, rotating and translating. Importantly this exploration is done in the context of a configuration of blocks. The spatial relationship

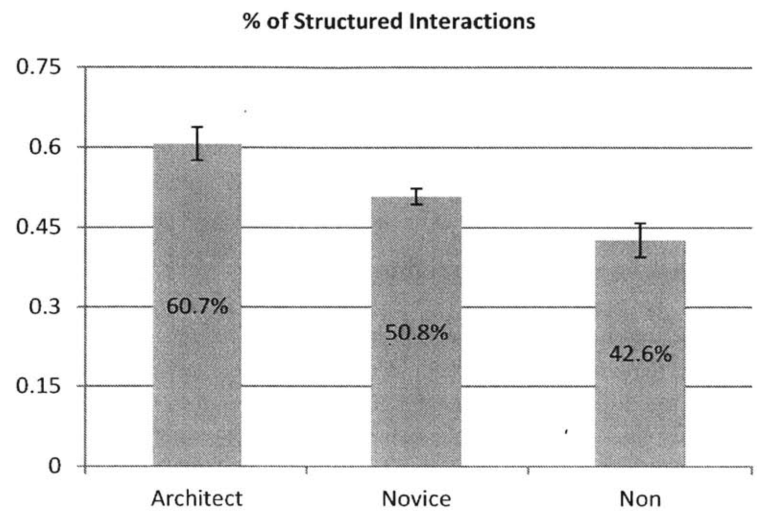


Figure 5.19 Experts had the highest percentage of structured actions compared to the other two groups.

between blocks is the focus, not the blocks themselves. The non-designers moved the blocks around however they did so in isolation or in a way that organized similar blocks together. They spent on average more time than the novices and architects in managing the work space.

In addition, architects in my study were more selective in which blocks they would keep in their configuration and also, importantly, they would more frequently remove blocks as their ideas changed. Working forwards and backwards would seem to be important to the architects. The novice and non-designers would more often keep blocks in their models accumulating more and more blocks as their design progressed. Characterizing this interaction result as setting up better experiments may explain the finding in terms of having more specific design intention, with what one is looking for. The architects were most clear about this of the three groups. They articulated strategies in terms of the material with which they were working and set about actions that could help them make a decision.

Lastly the architects' interactions overall were more structured. They worked for longer periods of time doing more actions on individual blocks than the novices or non-designers. In an exploratory task, architects think deeper with the material in hand. The higher degree of structure also indicates a more intentional interaction with the material. With the architects, there are fewer instances of rogue interactions. This is not the case with the non-designers. Their interactions can be characterized as meandering from one block to the next.

CHAPTER 6

Discussion

Implications for Material-based Robotic Interaction

"The world is its own best model."

-Rodney Brooks

6.1 Introduction

In this chapter I explore how robotic tools can enhance a designer's material interaction potential in exploratory model making. I first relate the findings from the design experiment in Chapter 4 and 5 to how a robotic arm could be programmed as an interactive partner in a similar blocks world scenario. My experiment findings suggest that an alternative approach to computational design and fabrication tools is needed if we are to support this kind of hands-on model making activity. The key difference is my vision for designers to work physically with computational processes instead of just visually through the representation of objects or processes on a computer screen. My approach is based on real-time robotic interaction, what I call material-based robotic interaction (Figure 6.1). I take inspiration from Rodney Brooks' famous line, "the world is its own best model." In saying this Brooks was arguing that the representationalist approach of robotics research of his day was creating unnecessary abstractions by duplicating the external environment with in an internal model, a representation of the environment. According to this approach one would first painstakingly define as many aspects of the robot's external environment and then create actions in it that could respond. Instead, Brooks was building robots that didn't need internal models of the external world, but rather relied on action in the world to build up an understanding it. Action led to a representation, not the other way around.

Of course, designers need to work visually with representations—this is what they do. According to Visser, designers " " (Visser 2009 pg x). However designers also with work material. Knight and Stiny argue, "We view designing not as an intellectual activity in which script in advance what we do and what can happen, but as a kind of making itself, an activity that demands perceptual, bodily engagements with materials in the world" (2015). However, I believe the way designers currently work with computers to make physical models is very limited in terms of their ability to 'think with their hands', the 'embodied cognition' described in Chapter 3. For example, in the typical digital fabrication workflow common today, one needs to first build up a model on the computer screen—the design—and then 'export' the design to a machine which can make it physical, whether as parts or as a whole. Much progress has been made in this digital-to-physical design translation approach. One of the earliest examples of this was the *Digitally Fabricated House for New Orleans* project from the Museum of Modern Art's 2008 exhibition, *Home Delivery: Fabricating the Modern Dwelling* (Bergdoll and Christensen 2008). This project illustrated the potential to take any particular design shape as represented on a computer screen and then translate it into a set of discrete machineable parts which could be later assembled, presumably someday by machines such as robots. What is important to understand in this approach is that the design work is already finished once it's time to work with the physical material. Working with physical material in this approach is assembly only, meaning no further modifications to the parts or the overall design may be introduced. I argue that every digital fabrication project since this project follows essentially the same approach. A design is first created on screen and then translated into physical

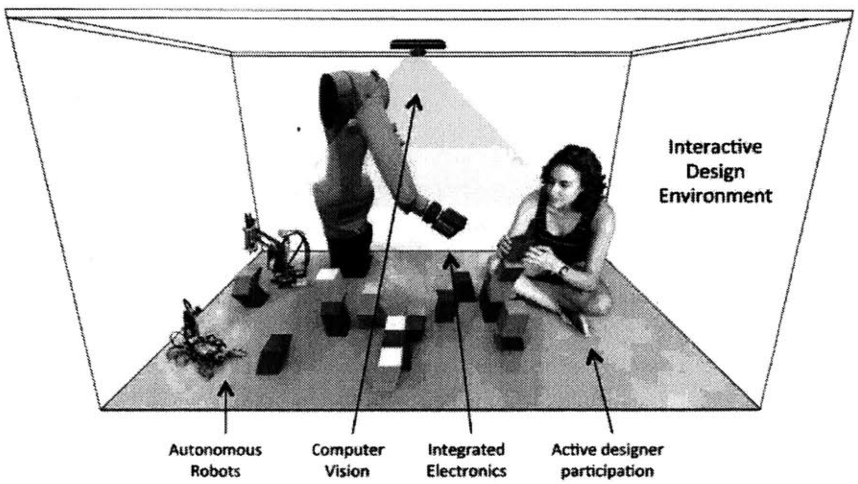


Figure 6.1 Vision for an interactive design environment

material. The difference is only in degree, not in kind. Why is this? Why, when working within a computational design process, must material interaction be limited to assembly only?

As made apparent in my experiment there are numerous ways of working with material in hand beyond assembly and designers exploit this multitude of material interaction to generate new ideas on the fly. Physical computational tools such as robotic manipulator arms present an opportunity to enhance this kind of interactive manipulation process. My vision for robotic aided model making presents an alternative approach to working with computational tools, namely one that doesn't necessitate a computer screen, at least as the initial or only means for generating and representing a design. The physical material model is its own best model. Its creation over time, as material is added, subtracted, modified and relocated in the workspace should be a focus of physical computing tools.

With this in mind I present an application of my research findings through a computer program in which a robotic arm is equipped with a vision system that is capable of recognizing changes to a design model and its environment and also capable of generating on-the-fly commands for object manipulation, all in real-time. The designer doesn't work at the computer to generate a design and then watch a robot assemble it. Rather, the designer, through material manipulation, controls and generates the robot's actions over time as the design model develops. I say 'we' here because I was fortunate enough to work with many talented undergraduate research assistants who helped with the programming, without whom this would not have been possible: Dana Gretton, Steven Homberg, Jaguar Kristeller, Rachel Rotteveel, and Raghavasimhan Sankaranarayanan. One pilot program is presented and three visions for interactive programs are presented in which a designer can work back-and-forth with a robotic arm to make simple configurations of material objects.

6.1.1 Implications for robots in exploratory model making

Technological advances often drive research in design studies. One of the first studies of how computers could enhance design activity was the creation of a tool called Sketch Pad, developed by Donald Sutherland at MIT in the 1960s. This was one of the earliest examples of a graphical user interface. Ever since, visualizing the design form has become the primary use of computers; it has been the focus of CAD for the last 40 years. Computers have been used to visualize form and furthermore, automate material manipulation through CAD-CAM technologies. However, in most applications, the 'design' work is completed on a computer screen via a GUI and then is exported to another machine for making the design physical with materials. This is the central premise behind 3D printing: a design is visualized on the screen and then printed out with deposited layering. But what if there was another way to use computers? What if we worked with computers via material interactions?

With robotics we have the opportunity to go beyond visualization and the typical CAD-CAM work flow. We can think about how material interaction itself can be enhanced and automated, and not just its representation on a screen. In particular, robotic arms may be integrated into the stages of a design process where ideas are still being formed.

6.2 Supporting a Designer's Material Interaction

As I observed in my experiment there are many kinds of body-material interactions in exploratory model making activity. Designers explore, assemble, manage, add, modify, subtract, and relocate materials as they construct physical models. Even in a simplified blocks world scenario these interactions are unpredictable, yet can be formalized in simple terms of picking, transforming, and placing blocks. Material must start from one location and end in another location and it can be transformed along the way. As digital tools become more integrated and distributed out into the design environment, e.g. robotic manipulator arms, integrated electronics, vision and tactile sensing technology, design researchers have the opportunity to consider how to support and enhance embodied design thinking. Tracking block locations and orientations, tracking configuration states and workspace conditions will be necessary. New research questions arise: does a robot manipulator arm replace the designer's interactions? Do physical materials themselves become programmable? Importantly, how does the designer communicate intention, especially without the use of a computer screen?

To address these questions I will re-present the key findings from the experiment in terms of how a robotic arm could enhance these material interactions. Instead of replacing the designer's interaction, I believe that a robotic arm could be thought of as a partner or third arm in a creative process.

6.2.1 Move Experiments: Trial and Error Interaction

The architects in my experiment provided themselves with potential solutions to consider *while* they worked. It wasn't that they made multiple models, but rather they tested (and often rejected) blocks locations and orientations within the configuration throughout the process. This result is captured in terms of the lower percentage of Test:Accept interactions and higher percentage of Test:Reject and Test:Eject (Figure 5.17). This is an important point: when making physical models to explore new ideas designers don't just create a mental image of a model and then execute its construction physically. One of the novices nicely stated this problem in terms of thinking in 2D vs 3D:

> "I realized especially when I dealing with shapes I'm not familiar with...if something's in 2D I can imagine it in my mind...but if its 3D I don't know what kind of problems I'm going to have so I feel like I can't prepare for it...I just have to do it."

Apparently three dimensional objects and spatial relationships between them are difficult to imagine so designers instead think through *making* the model. They interact over time with the model by adding, subtracting, relocating and modifying the materials. Neither do they only create a model and then inspect and modify it. Their testing happened in real-time as the model itself developed, piece by piece. Through translation and rotation alone they could explore many unique block orientations and locations thus changing the model. A physical computing system should be able to capture and help support this dynamic process with the material. The system should help designers see new relationships through material manipulation.

Considering the material quality is important. The blocks given afforded this kind of trial and error interaction. The architects picked up on this quality of the material and used it to their advantage more so than the novices and non-designers. As one architect pointed out:

> "I like that these create an 'outdoor/indoor'...a kind of exterior spatial definition and an interior spatial definition...it's super strong...and you don't have to do much to let them do that...which is nice."

'Doing' in this case means rotating and translating the blocks. The other novices and non-designers of course did this too and with similar frequency in terms of overall actions/minute. However, it is the *kind* of interactions that the architects did that are important to understand.

6.2.2 Model-Centric Interaction

It was *modify* interactions that the architects and novice designers did with more frequency than the non-designers. And importantly, these interactions took place at the configuration. Non designers especially were more concerned with the state of individual blocks in isolation and across the site, as stated in terms of their Relocate interactions (Figures 5.11 and 5.13). The architects did not spend as much time relocating the blocks around the site. Their focus remained on the model as much as possible. In addition, their *add* and *subtract* interactions were more frequently coupled with Modify interactions in terms of Test:Accept, Test:Reject and Test:Eject interactions (Figure 5.17). Through interaction with the material the model was constantly changing. A physical computing system should be able to keep track of the model's states over time.

6.2.3 Unpredictable modeling

When making the physical models the architects worked in very short cycles of move experiments. My coding scheme defined these cycles at the level of picking, transforming, and placing blocks. Importantly, architects pick blocks without knowing what they will do next. Only after they test them in various orientations and locations can they make the decision whether or not to place the block in the configuration. In other words, they act before they think. Or at least they start an interaction before they know what it will do to the model in the environment. This short cycle coupled with unpredictability is the key advantage of working with one's hands. Architects demonstrated specific embodied strategies that helped them manage this unpredictability and come to a design solution.

Making complex physical models in real time is difficult – it's hard to predict outcomes of joining materials together in 3D environments, as one subject pointed out, we assume because it's hard to judge distances, angles and sequences of actions over time. Typically one has to plan out a model in advance, completing it entirely before building it physically. As another participant put it, designers think globally and then use computational tools to divide the geometry into unique units that can be manufactured and later assembled.

6.2.4 Epistemic action: moving the body around the model

Though I didn't present this analysis in Chapter 5, I also observed that the architects moved themselves around the site model more frequently. Reorienting their head close to the model was common. When looking at the models there was not a single vantage point taken by the architects. What does this gain the model-maker? I believe it provides a better picture of the 3D environment in which they are working. Sitting still, one will have a biased point of view. I call these kinds of movements epistemic because these actions do not directly support the goal of building a model, but rather may make it easier to see how blocks fit together and possibly see potential positions.

6.3 Limitations of Current CAD-CAM Design Production

The rapid and unpredictable interactive making process cannot be automated with current computing technology. In CAD-CAM prototyping, whether with additive processes such as 3D printing, robotic pick and place, or subtractive processes like CNC milling, every step along the way is known in advance. The physical making process happens *after* design thinking has taken place on the computer screen, or elsewhere. I do not intend for robotic manipulators to replace the human in model making activity. Rather, I consider how technology can support real-time model making.

6.3.1 Related Work

Recent years have seen rapid expansion of physical computing devices as a result of cheap and readily available electrical circuits, sensors, and interfaces like Arduino, Kinect, and Kuka robotic arms (Figure 3) (Braumann and Cokcan, 2012). Some tools situate the control and design interface of digital fabrication tools such as CNC routers directly on the machine and allow for real-time control of the cutting bit through motion tracking technologies (Willis et al, 2010; Willis et al, 2011). Zoran and Paradiso constructed a handheld Dremel-like digital sculpting tool called FreeD enabling a novice user to directly engage with sculpting material through the aid of computational feedback to correct movement errors based on a digital design (2013). Braumann and Cokcan explore strategies for robotic arm user interfaces including touch-screen sliders and gesture-based motion-capture control mechanisms (2012).

Such tools and projects demonstrate how physical computation technologies can engage the body by means of haptic, motion, and infrared sensors; however, little attention has been given to the relationship between design, thinking and physical computing. The examples above are tools for sketching, sculpting, and tracing. What is needed for physical computation tools to become useful for expanding design cognition is a framework of interaction potential of how designers think with their bodies through movement.

While there are certain advantages with computer-aided design and manufacturing—precision, speed, complex geometric forms, etc.—why can we not have computational making processes and design thinking at the same time? The problem is two-fold. First, is a technical problem: CAM tools are not aware of the surrounding environment. They have no sensing capabilities. Once you start a CNC machine going on its toolpath, it doesn't matter if there's material there or not, it just proceeds to the next waypoint as programmed.

6.4 Interaction via Material Manipulation and Spatial Relationships

Designers do not need to directly interact with a robotic arm or vision system, such as through gesture or hand signals. Interaction, in my use of the term, is through manipulation of the model, through is materials and spatial relationships. The robot should be able to 'see' or otherwise 'sense' the model being made and see the interactions. The model development can be tracked in terms of geometry as well as the designer's interactions over time with the configuration (adding, subtracting, relocating and modifying blocks). It should be able to discern the individual parts being used and detect the emergence of a configuration separate from a pile of sorted or unsorted blocks. It should also be able to undo interactions with blocks returning the model to previous states. This would require robotic interaction with the model.

6.4.1 Automating the formation of geometric spatial relationships

For some interactions a robotic arm could perform better than a human. Such interactions could be automated and done on behalf of the designer. Interactions that involve global arrangements of blocks are particularly difficult for humans as I tested (See Figure 6.2 and 6.3). A useful starting point for considering what kinds of actions would be beneficial in a physical computing system would be traditional CAD commands that architects are already used to working with. These include linear, rectangular, and polar arrays, as well as rotations in different axes, and also functions that create reflections of objects, and segmenting space.

Prior to the blocks world experiment I gave the participants short manipulation tasks to help them become familiar with the parallelepiped blocks (Figure 6.2). These tasks included:

- **Mirror:** starting with a given configuration of a set of blocks, make a mirror configuration across a given center line.
- **Copy and Scale:** starting with a given configuration of blocks, make a ½ scale copy of the configuration with a set of provided blocks.
- **Flip:** take a given configuration of blocks and flip them all 180 degrees so that the blocks remain in the same orientation relative to each other
- **Stack:** using nine blocks provide, stack the blocks as tall as you can.

These computational tasks were difficult for most of the participants to complete manually, indicated by the amount of time spent completing the task and the accuracy of their operations. For example, in the flip task the subjects were asked to rotate the entire configuration of blocks about a particular axis. As we expected, in doing this many subjects flipped individual blocks into place. However in attempting this many would try and undo their flip to recall its previous position. Often they could not recall the starting position. It seems that remembering previous positions of 3D objects is difficult. In another task, subjects were asked to make a mirror configuration of blocks given a starting configuration. Most subjects struggled with correctly arranging the blocks. It seems that judging distances and angles across space is difficult.

6.4.2 Enhancing interaction primitives and restructuring sequences

My vision is to integrate robotic tools further upstream in the design process. The challenge is to support the dynamic and unpredictable nature of hands-on model making. This requires that a material and its interaction potential be defined. In blocks world the material interaction potential is rotation and translation. Because my blocks are parallelepiped shapes it is difficult to predict the outcome of these simple manipulations. With a robotic interaction system material should be defined into interaction classes. Material can be rotated and translated, but

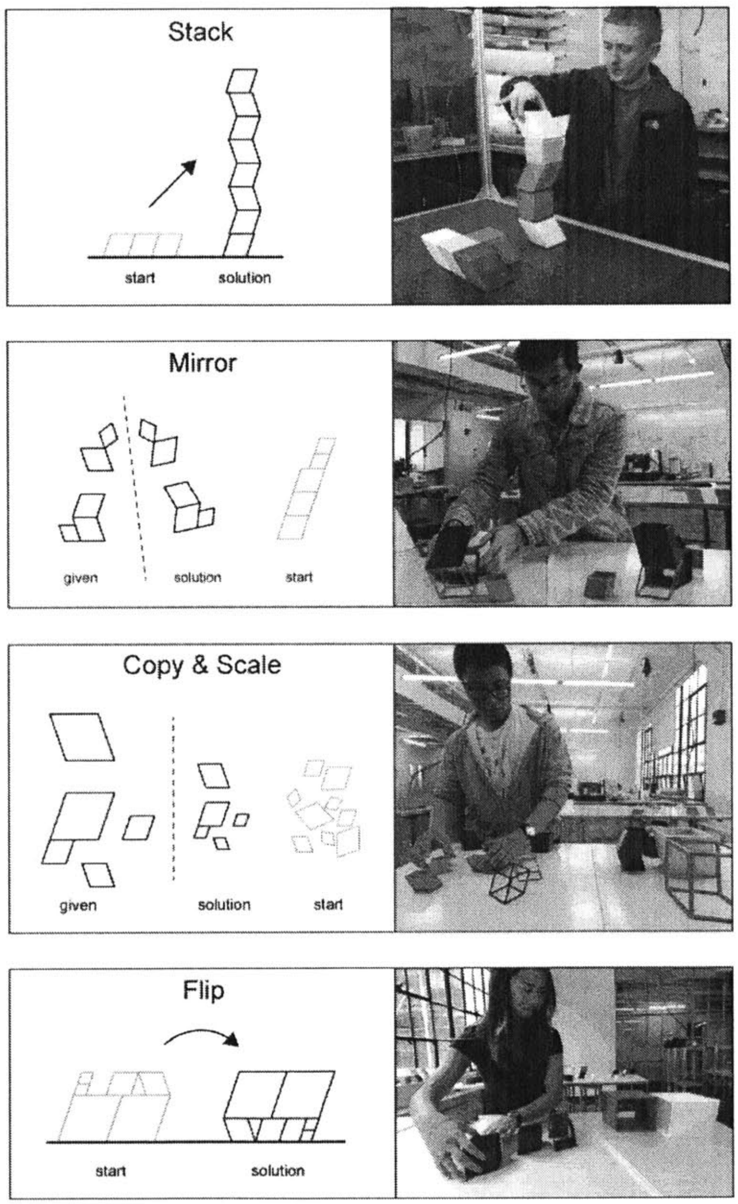


Figure 6.2: Participants were tested on their ability to perform computational operations such as creating mirror configurations, copies, flips and stacks.

also cut, torn, or split. Some material can be folded or bent while other materials can be poured.

This process is inherently different than the digital fabrication process. Because model definitions unfold piece by piece, an interactive robotic system must first of all be able to recognize the model as it changes over time. As new forms emerge designers set up embodied interaction experiments to see possibilities and make design decisions. As my study shows architects do this in a variety of ways that can be coded as material interaction primitives and sequences. Robotic manipulation tools can computationally enhance primitive interactions. The primitives are constructed from three actions: pick, transform and place.

Not only can speed and precision be enhanced but also transformation variety and complexity. The blocks in our study were relatively simple and easy to manipulate. Forming relationships between more complex and varied geometry would prove challenging for humans but simple for robot manipulators.

6.4.3 Pick and Place: Typical use of robotic arm

Consider if the experiment was to be carried out using a robotic arm manipulator with state of the art design visualization software. The design work would take place in a CAD environment. In this virtual setting, subjects could arrangement the blocks in all the same ways possible as with physical interaction. They could add and subtract blocks, modify them through rotations and translations. They could do so much more though. They could duplicate blocks, scale blocks, delete blocks, etc., performing many computational processes that are not possible outside the computer.

However, in order to make it physical, the beginning state the final state of each block would need to be modeled in the computer. Where did each block come from? Then a simulation program could be run to visually verify the motion path for each block on the screen. In what manner would the block travel from its starting point to its end point? The sequence of block arrangements would also need to be modeled. After this, in the physical environment of the robotic arm and work surface, each block would need to be placed in the exact same location as modeled in the CAD environment. The work surface upon which the model would be assembled would also need to be cleared of any obstructions. With the real world matching the virtual world, the robot arm could pick and place each of the blocks to assemble the model. At this point, the designer is no longer able to interact with the model.

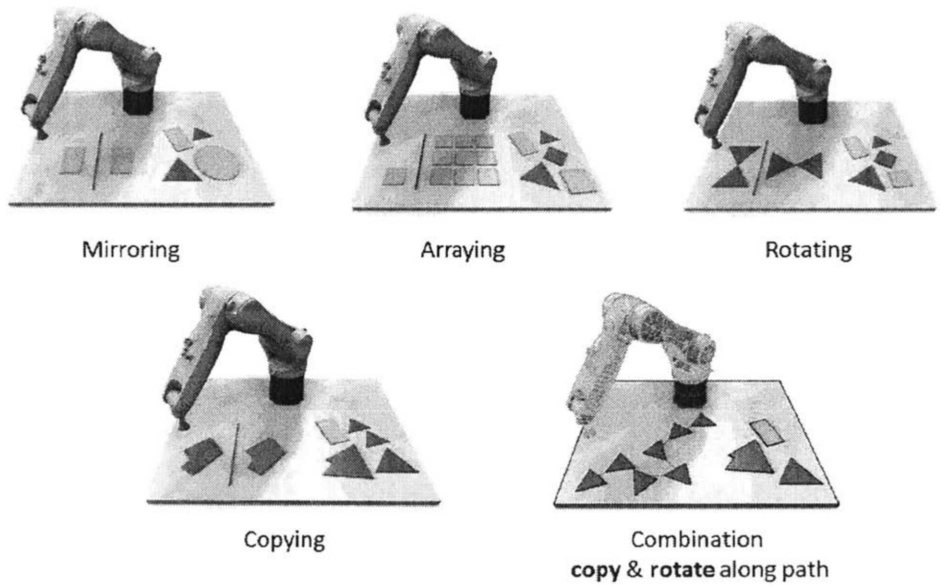


Figure 6.3: A robotic arm could be programmed to see a shape and create a mirror relationship, or an array, rotation, copy, or any combination.

One may test many possible block locations on the computer, however, when it came time to program the motion path of the robot manipulator arm, one would not include all of the in-between stages. One would take the final configuration only and program the beginning state and end state of each block. One would optimize the motion paths to be as few as possible. It is possible that you could create a one-block-at-a-time program. In this case the starting point of each block would still need to be known. The robot arm would also need to avoid the updated locations of the previously-placed blocks.

What is gained by this kind of process though? The robotic arm is essentially being used as a remotely controlled device. The advantages of working with one's hands are taken away as well as the advantage of the robot. The advantage of working with ones hands is that one doesn't need to know in advance of movement what the action will be in order to make the move. When you pick up a block with your hand you don't need to know where you will put it; you just know you want to do something with it. In robotic programming one has to know both the start point and end point of the motion path. It may be the same location for start and end point, but nevertheless it needs to be calculated; the robot needs to know where to stop. With ones hands this is not the case because the end point location is indeterminate. This is evidenced by the fact that with our video analysis we have to fast forward until after the place action in order to record what it was. Accordingly, it may be that design thinking occurs somewhere and some-when in between the pick location and place location.

This kind of interaction should be supported and complimented by the environment. When one does know in advance what is wanted of the blocks, then the robot can be called into action. "I want 9 blocks arrayed," for example, may be command. Computational operations such as these would be better off done by the environment. Whereas if one doesn't know what he wants from a block, he would be better off doing it with his own hands. Through interaction with the blocks a new idea may come.

6.5 Pilot Program for an Interactive Robotic Arm

As we've seen though design making can be much more. It involves an ever changing solution and unpredictable interactions. In order for digital tools to support and enhance interactive model making, there needs to be an integrated vision system or self-aware components that can be updated at every change. However there are still computational operations that can serve a designer. These must happen in real time. Operations such as copying, arraying, reflecting, and dividing can be done by the robot system (Figure 6.3).

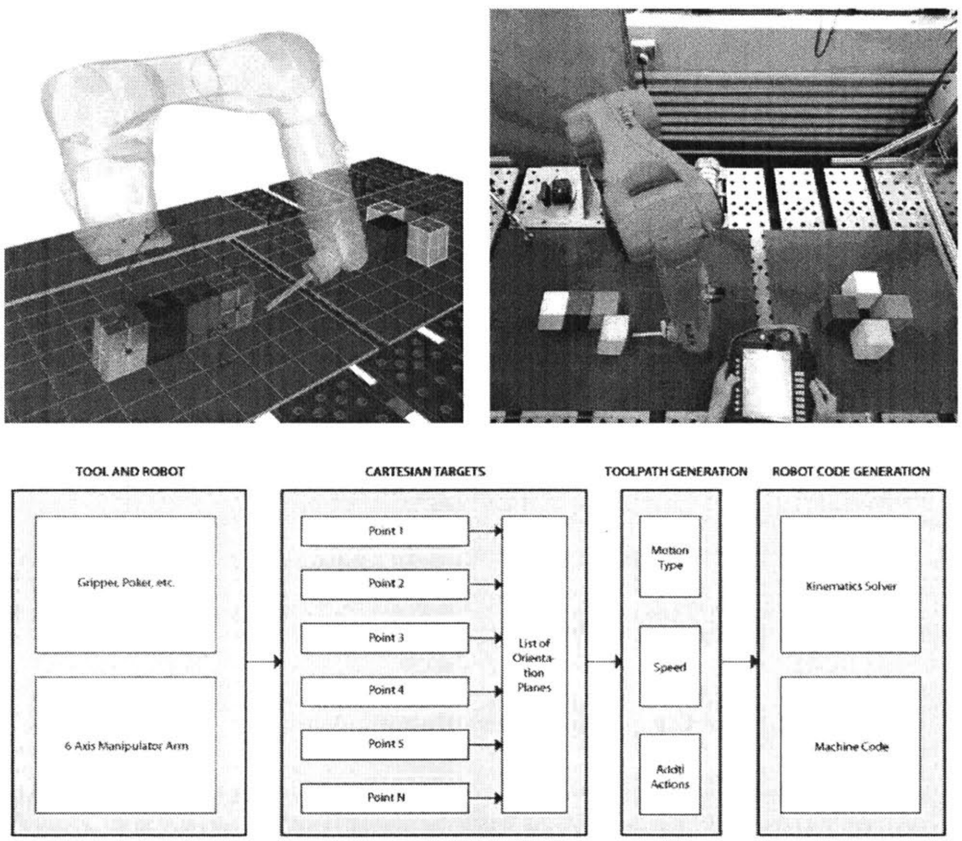


Figure 6.4: A typical program sequence for a robotic manipulator arm.

As a starting point for an interactive robotic manipulator system, we created a program that could translate flat extruded shapes across a flat work surface. These shapes included simple polygons such as squares, circles, equilateral triangles, and pentagons. Our program could recognize and distinguish each of these shapes and quantify their location in XY coordinates. Based on these locations the robotic arm could 'see' the shapes and generate commands to pick them up with a suction gripper and place them a predefined relative distance away. Our interactive system was composed of my components (Figure 6.5).

6.5.1 Interactive Robotic System Components

- **Robotic manipulator arm:** Kuka 6-axis robotic arm, various grippers for pick and placing material, fixed base location
- **Robot controller computer:** Kuka controller CPU generates inverse kinematics for each arm operation
- **Remote computer:** ROS, packages the vision and command generation
- **World/site:** flat work area within reach of arm, painted white
- **Camera and Object Recognition System:** webcam capable of HD image capturing
- **Material:** flat painted shapes including squares, triangles, circles and pentagons

6.5.2 Robotic manipulator arm and controller computer

Our robotic arm is the Kuka Agilus KR6 R900 SIXX. The controller is the KR C4 version. This is a six axis arm typically used in industrial/manufacturing settings. The arm is very robust, accurate, and fast. This is ideal for its intended applications, such as repeating the same task continuously, but we ran into many difficulties in programming it to perform more agile and varied operations.

6.5.3 Remote computer running Robot Operating System (ROS)

This is desktop computer connected to the Kuka controller computer via TCP/IP (Ethernet). We used the Robot Operating System platform to package the commands and vision systems and communicate with the Kuka controller. We used an open source program to set up the real-time communication called, JOpenShoVar. This project was originally developed by Massimiliano Fago.

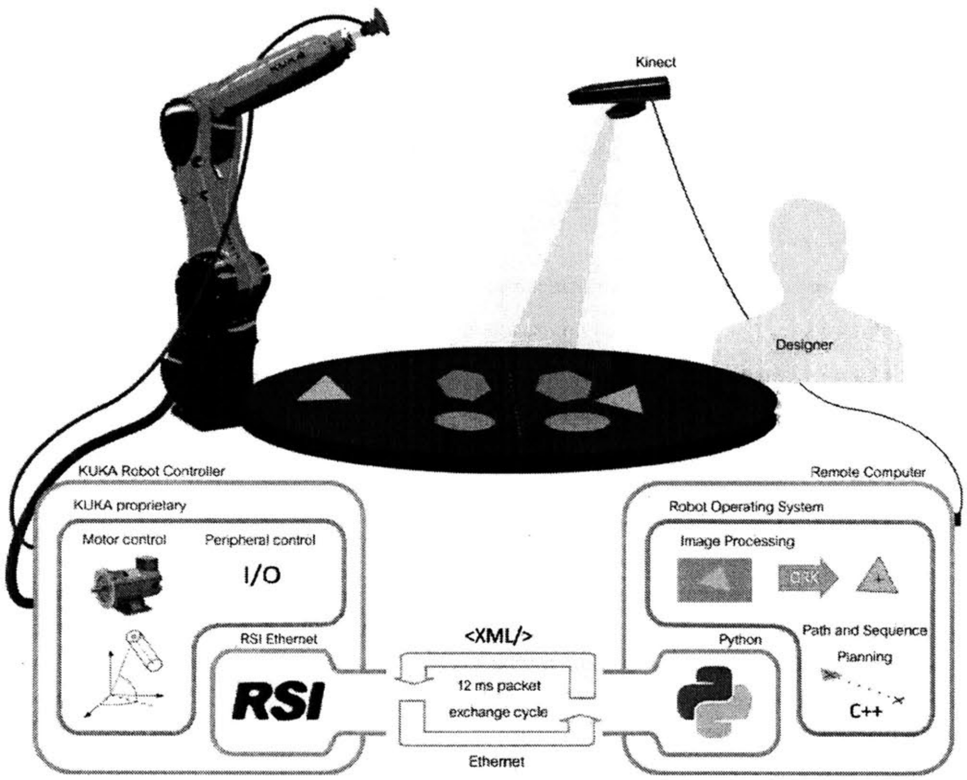


Figure 6.5: The proposed interactive system includes a camera, robotic arm coupled with an ethernet connection between the robot controller computer and the Robot Operating System to allow for real-time motion planning. Image by Dana Gretton.

Its documentation can be found here: http://aauc-mechlab.github.io/JOpenShowVar/. We developed 5 nodes within ROS that worked together to run the program and communicate with the Kuka controller.

1. PTPServer
2. GripServer
3. Interface wrapper
4. Shape recognition server
5. Control node

6.5.4 A site for picking and placing material

All activity must take place on a location that is both visible to and reachable by the designer, visible to the camera, and reachable by the robotic arm. A work area should be delineated so that this work zone is clear. With a small arm such as the one we used, the work zone as a flat surface is roughly 2.5' x 3'. A separate area for material storage was created and delineated (Figure 6.6) for both the robot and the designer.

6.5.5 Camera and object recognition algorithm

In our pilot program a designer can manipulate and arrange only flat shapes such as circles, squares, and triangles. This constraint is set by the shape recognition algorithm. In our case the camera is mounted above the workspace and can only distinguish shapes on a horizontal plane. The shapes are made in advance creating a stock pile at the beginning of the design session. In order for the vision system to recognize the shapes, it must first be told what to look for.

Our object recognition algorithm could only detect individual shapes and failed to detect shapes that were directly touching each other. At least a 1/4"' separation was required, which was a factor of the camera resolution (Figure 6.7). The camera was only used to generate .jpg images, not video. The image was captured before any action was generated while the robotic arm and designer's arm were out of the frame of the image. Even and diffuse lighting was required to prevent hard shadows cast by the shapes.

6.5.6 Operation: translating shapes across a surface

In our pilot program the robotic arm can only translate shapes across a flat surface. Only a single video was recorded that captured the robot in action, which can be found at the following URL: https://www.youtube.com/watch?v=kMbp5wqybhY. A configuration a shapes may be first be arranged by the designer and then the arm can pick, translate and place

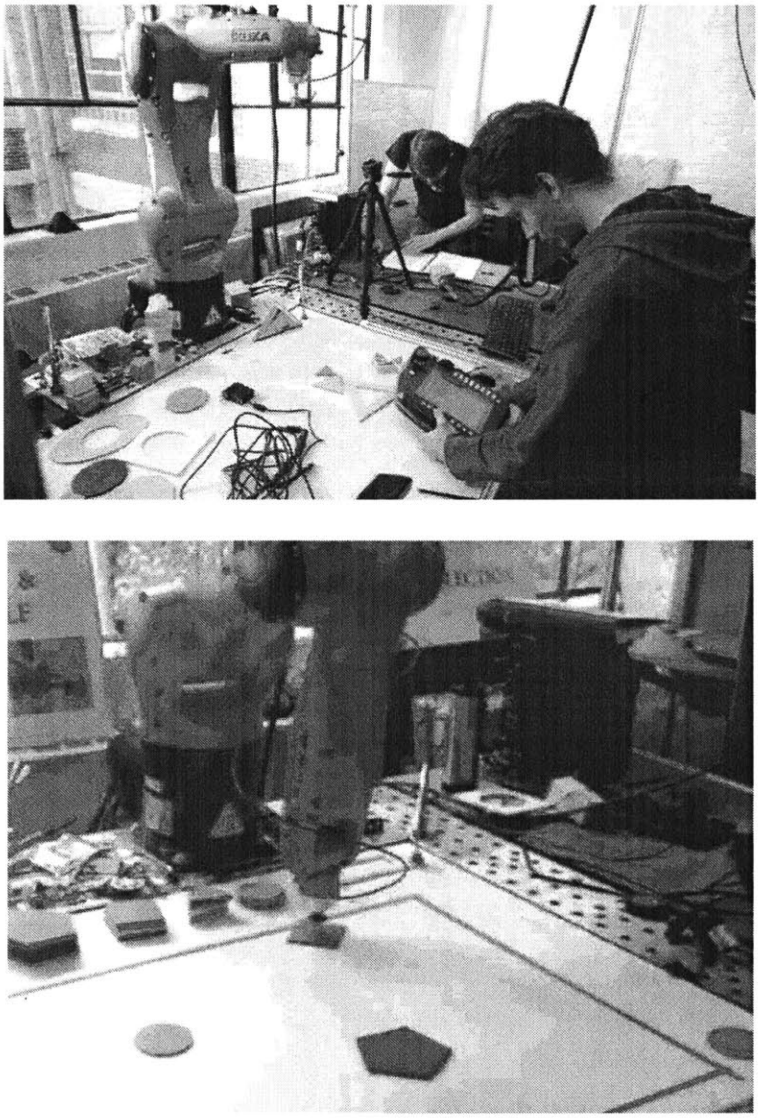


Figure: 6.6 Top, undergraduate researchers Dana Gretton and Steven Homberg testing the vision system; Bottom, image of pick and place action with simple shapes.

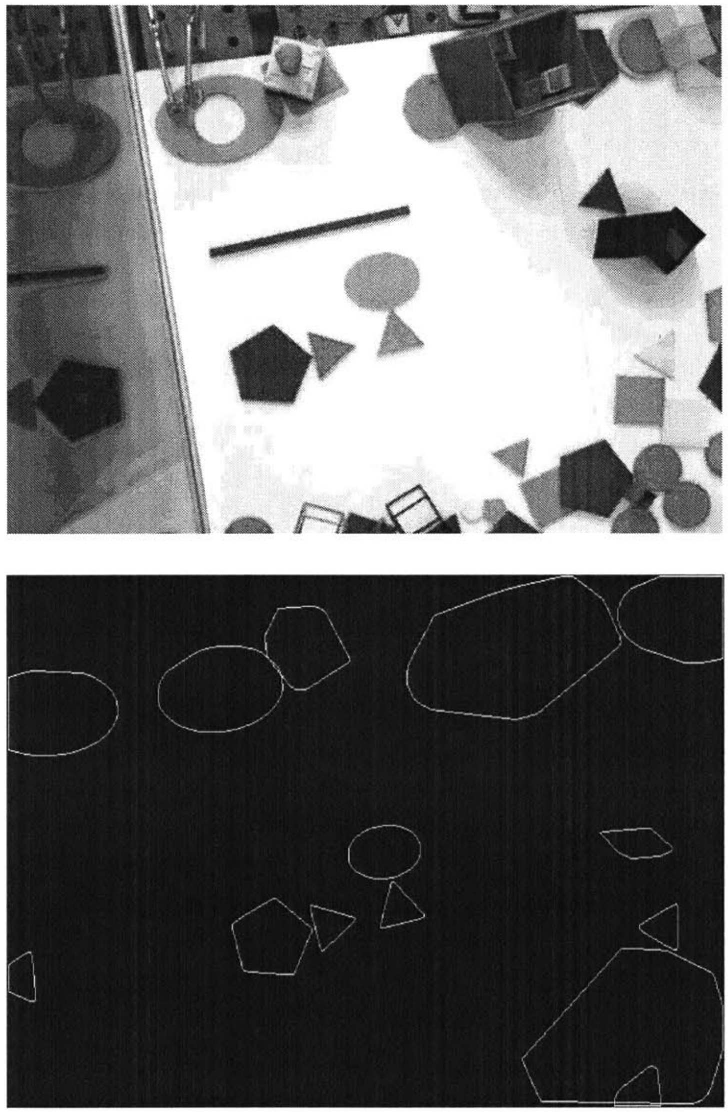


Figure 6.7: Shape detection algorithms are needed to distinguish shapes. Images by Steven Homberg.

each of the shapes at a new, predefined location, relative to each object. The distance of the translation is determined in advance. Any number of shapes could be translated. The object recognition algorithm could detect and count how many shapes were in the image. The operation goes as follows:

1. **Run the program on the Kuka controller:** someone has to be running this program through the entire set of actions. We did not run the program in automatic mode, which allows a program to proceed without the safety triggers engaged.
2. **Shape placement:** the designer places given shapes on the site. Importantly, the designer must know in advance the direction and magnitude of the translation so that shapes are not placed too close to a boundary that would cause the robotic arm to extend beyond its reach capacity.
3. **Image capture:** after a predetermined amount of time following the shape placement, the program would take a picture of the site. The object recognition algorithm would create shape outlines and determine which shape was what. It would then count the shapes and determine the center points of each shape, which would become the pick location.
4. **Generate pick/place command:** Based on the image capture, the program would generate commands to define the number of pick locations. This was communicated to the Kuka controller so that it could create the needed inverse kinematics (IK) for each operation. The pick/place command was composed of the follow sub-routines:
   a. Create 3 sets of IKs for the center point X,Y, and Z coordinates of the shape. Z coordinates were fixed based on the work surface height and the approach/retract locations directly above each point, thus three sets of locations were needed for the pick location and the place location. The orientation for each axis at each point was also required, which was fixed in our program since there was no rotation needed to translate the shapes. In our case, the orientation of the suction gripper was always pointed normal to the work surface.
   b. Activate and release suction gripper. At the XYZ location above the pick location and above the place location the suction gripper needed to turned on and off, respectively.
   c. Acknowledge success of each shape translation. Did the arm successfully translate the number of shapes that were found? If not, continue program until all shapes have been translated.
5. **Return arm to home position**

6.6 Visions for an Interactive Robotic Arm in Design Activity

This simple pilot program could have many applications. Because translating shapes in an XY plane is of limited functionality, I have envisioned what the next steps and functionality level of an interactive program could involve. The primary challenge addressed is how to control the robotic arm and convey intention. If a designer is to work interactively with a robotic arm these challenges will need to be met. How does one communicate to the robot the desired action on material without expending as much energy in communicating the task as it would take to simply do the task oneself? Some research approaches have suggested that control would take place through gesture. This however is of limited functionality as the robot could mimic actual motion while not really communicating the material interaction.

My approach is to control the robotic arm through material interaction and forming spatial relationships, based on the primitive interactions described in Chapter 5: Adding, Subtracting, Modifying, and Relocating material. I have developed two approaches. The first is creating bounded spatial relationships based on global geometric operations. These operations can include reflections, arrays, and rotations. The second approach is to use rule based operations that the robot can detect and mimic. Each of these is described in detail below.

I have developed demonstration videos to illustrate these potential interaction programs. These videos can be seen at the following URL: https://www.youtube.com/channel/UCubcL661MmNXpPDNqR4bpng.

As with the pilot program the demonstrations presented here are with manipulation of flat shapes, however the potential for a multi-axis robot arm opens up a more three dimensional material manipulation. The primary constraint in this work is the vision system. Detecting three dimensional shapes is a non-trivial problem that we did not attempt to solve.

6.6.1 Creating bounded relationships through geometric reflections

The first approach is in creating bounded relationship between material that the designer manipulates and material that the robot manipulates. I illustrate this approach by forming geometric reflections that are created back and forth between the designer and robot (Figure 6.8).

1. **Designer places the material:** The designer places material anywhere on the work surface. The material needs to be in the bounds of the designer's and robotic arm's vision and reach.
2. **Robot sees the material:** A camera, in this case, mounted directly above the work surface, detects shapes with a certain region and creates outlines. It recognizes the shapes as squares, circles, triangles or pentagons. In this case the object recognition algorithm only recognized pre-determined shapes such as squares, triangle, and circles, however I can imagine more a more dynamic process for creating new shapes on the fly.
3. **Designer creates a spatial relationship:** by using a physical object, like a stick, what I call a control stick, the designer can set up a relationship between the material

placed down and future material placements. In this case the relationship is based on creating a center line for reflecting the shape configuration (see Figure 6.x).

4. **Robot sees the spatial relationship:** The vision system sees the control object placed down on the work surface and projects the material outlines in a reflection across the center line.
5. **Robot creates an action:** after recognizing the material shapes and configuration and spatial relationship, the robot generates a command to pick up new shapes that can be used to fulfill and place the shape in the reflected relationship. Any number of shapes can be picked and placed.
6. **Designer modifies materials and relationships:** After initial materials and relationships are defined, the designer can make changes to them such as adding, subtracting, or modifying the material, and repositioning the control stick to modify the reflection position.
7. **Robot sees new material arrangement and spatial relationships:** After changes have been made by the designer, the robot sees it again and generates new actions for updating the all the relationships.

These steps can be repeated until the designer is happy with the design, in this case, the arrangement of shapes. Multiple spatial relationships can be formed, modified, and taken away throughout the interaction process. What is important and useful about this approach is that the designer can explore the effects of reflections without having to manipulate each material object in the reflected relationship.

6.6.2 A variation of the bounded relationship: creating arrays

A second potential approach is related to creating bounded relationships but focuses on the idea that a designer's actions can be multiplied with the robotic arm thereby opening up time for him to perform other actions simultaneously. I illustrate this approach through the formation of object arrays (Figure 6.9). Arrays could include linear arrays, rectangular arrays or polar arrays. The process follows similar steps as in creating reflections; however a way to communicate which type of array and how many units will need to be communicated.

In my video demonstration I show how a 3x3 rectangular array would be created and modified over time. The designer sets an initial shape and the robot multiplies that shape placement by 9 times in a determined formation. Through the robotic arm the designer can control many more actions than his own. While the robot is operating the designer can begin seeing and thinking about new ideas in the material relationships. I demonstrate how a designer can begin sketching while the robot is in action. This is an idea of simultaneous multi-modal design thinking.

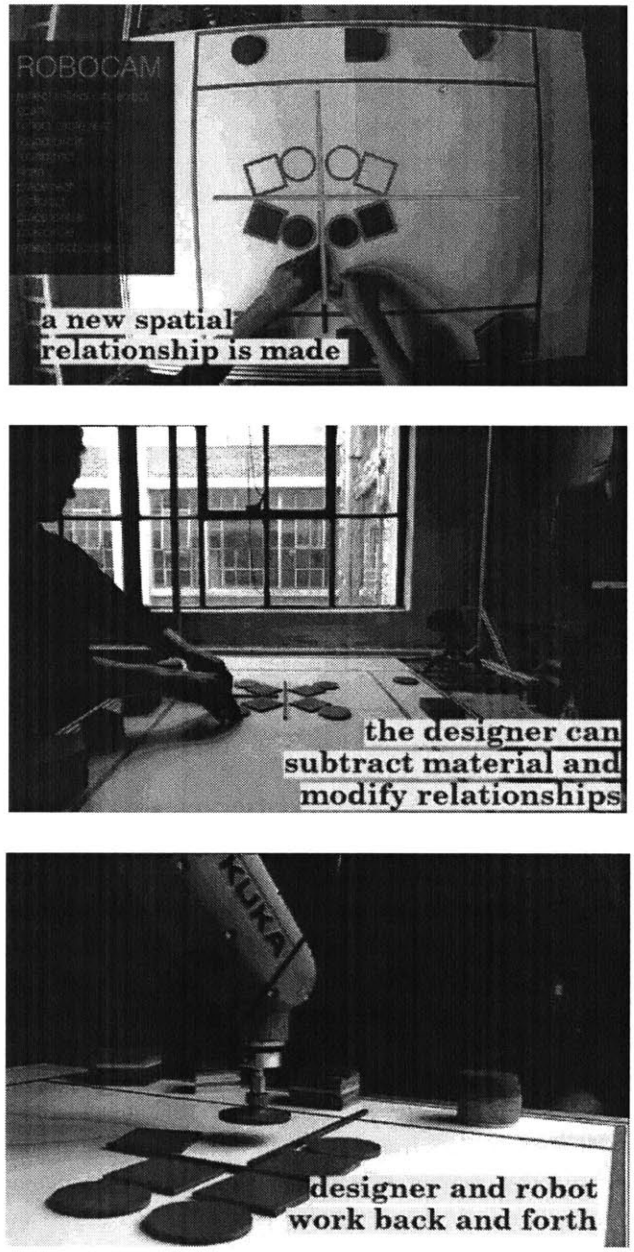


Figure 6.8 Creating bounded relationships such as reflections allow designers to work back and forth with the robotic arm.

6.6.3 Rule detection for block placement and relationships

The last approach I envision is to have the robotic vision system be able to detect geometric rules for shape relationships created by the designer and generate actions that copy such placement rules. For example, the designer may place a square shape next to another square shape (Figure 6.10). The particular placement can be characterized in terms of relationships between the shapes' boundaries, such as edge-to-edge or midpoint-to-edge. The robot sees this relationship as an action rule which can be duplicated with another shape that it can place (Figure 6.10). However, many different placement options may become available based on what the designer has constructed. For example, if the designer places two squares edge-to-edge, the robot then would see six new potential locations that could be chosen that would satisfy the rule. In my demonstration, the robot is programmed to randomly select any one of these locations.

This example illustrates an Add operation by the designer and therefore by the robot. However, Subtract and Modify operations can be characterized as placement rules as well. The designer could subtract a shape that is surrounded by two squares edge-to-edge. The robot would then need to find another situation in the configuration that fulfills this rule. If no other set of shapes does fulfill this rule, then the robot would have no action. Modify operations would similarly be executed.

6.7 Limitations

The preceding of examples of material-based robotic interaction illustrates only one kind of material interaction, that of arranging flat shapes on a flat surface. This of course is a very limited way of manipulating material and also it should be noted, not one that is common in typical design activity. This approach, of working with discrete objects as a design medium, is contrary to how many designers of today are used to working with computational processes, which in most cases involve working with visualizations on a flat computer screen.

Furthermore, shape manipulation requires that the shapes be pre-defined so that they can be recognized and duplicated by the robotic vision system. This introduces a highly constrained palette with which the designer can work. However, designers always work with material constraints, so if we are to program robots to work interactively we need to understand those constraints and develop specific interaction programs that can work within each of the material constraints identified. Different classes of material interaction can be developed. The manipulation of simple objects is a fundamental way that humans ordinarily interact in the real world. This is especially true at younger ages in human development.

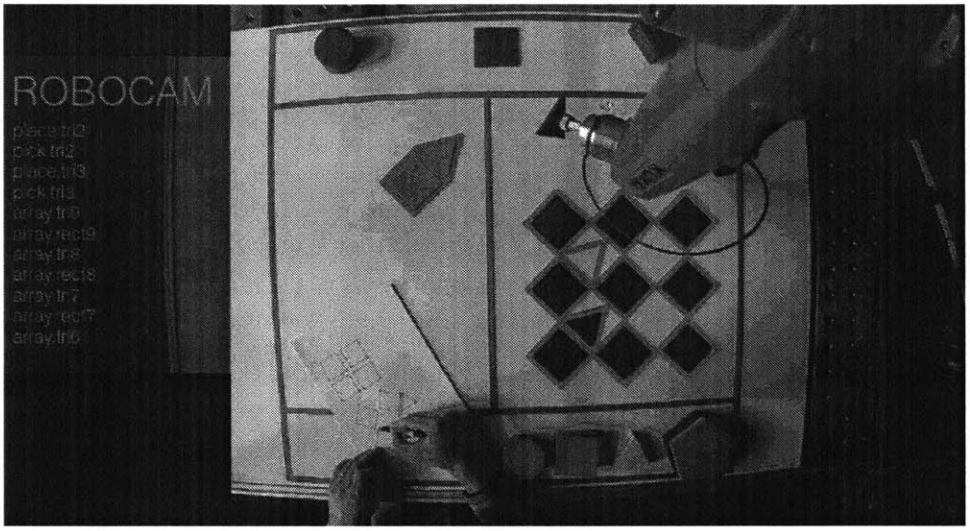


Figure 6.9 Creating bounded relationships such as arrays allow designers to work back and forth with the robotic arm.

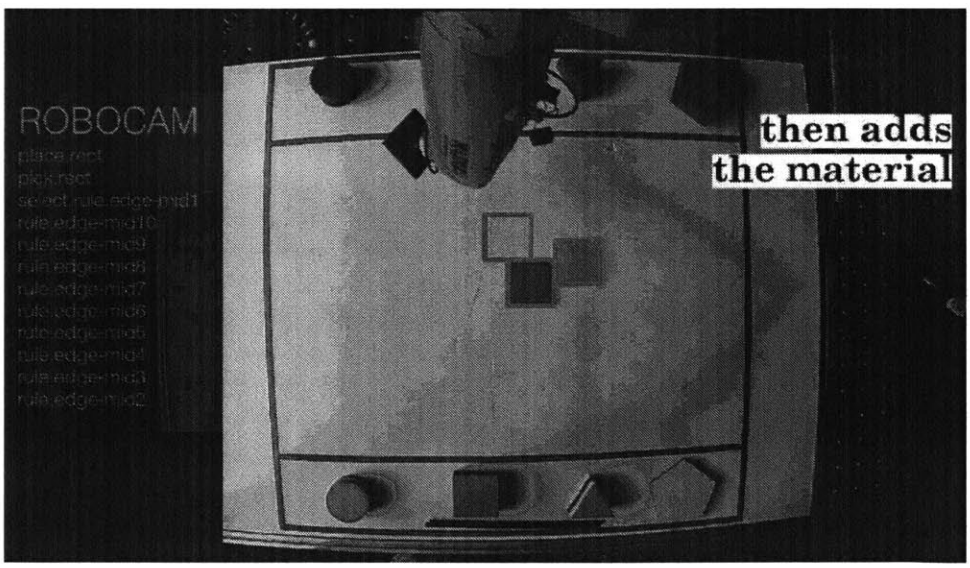


Figure 6.10 The robot detects a rule between the yellow and green shapes, edge-to-mid, then duplicates at another location as indicated by the red outline, and picks a square to place.

The shapes presented in the examples above are regular polygons that have been extruded and laser-cut out of sheet material. This limitation is due to the fact that the camera in the vision system is mounted directly above the work space, therefore it can only detect two dimensional shapes. However, three dimensional shapes should also be explored. This would require multiple or moving cameras. However the problem of object detection becomes exceedingly difficult, something that is still at the cutting edge of vision research. There is the possibility of mounting a camera onto the robotic arm which would allow it to scan the workspace from different points of view.

Lastly, building models with discrete objects also introduced a constraint of working in a piecemeal fashion. Designers do not always build up their models. They may begin with a whole then break down into smaller components. Working piecemeal as was done in the demonstration videos limits designers thinking with parts and wholes.

6.8 Summary

I have shown in this chapter the potential of material-based robotic interaction. Designers can work in real-time with a robotic arm that can see and manipulate shapes alongside the designer. Although this is a limited way of working with material, it represents a fundamental approach that needs to be addressed if interactive robotic systems are to become accepted into standard design practice. Further material interactions should be studied and classified according to how a robotic partner may manipulate it.

CHAPTER 7

Conclusion

Contributions, Impact, Limitations, and Future Work

"It's taken me all my life to learn what not to play."

-Dizzy Gillespie

7.1 Dissertation Summary

I believe that with the new physical computing technologies on the horizon like 3D printers, robotic manipulator arms, and environmental sensors there is potential to reconsider how the body impacts design thinking. In this work I demonstrated how experienced architects, in their physical interactions with material, can be distinguished from novices and non-designers in terms of simple physical computing vocabulary. I call this phenomenon physical design cognition, a kind of analog computation. With interactive robotics the physicality of material interaction can be computationally described and enhanced.

What I struggled with in my early work was how to capture and harness these qualities of analog computation without dismissing the value of digital computation. There is a long standing debate in architectural design regarding the value of digital and analog tools. See for example, the 2011 ACSA conference, *Hybridized Practices: Both the Analog and the Digital*. Authors in this conference questioned how they recapture the experiential qualities of analog tools and contrasted them with computational tools. Porter suggests that the discussion should be framed around computational versus formalized processes (Porter, 2011). Brillhart presents a study of design processes with and without computation to reveal how the brain works at "*creative, intuitive, and rational*" levels (Brillhart, 2011). Corser suggests that a hybrid process of digital computation such as parametric modeling and digital fabrication be coupled with analog physical modeling and form-making to create a more discovery-based design process (Corser, 2011). These positions reveal the common assumption that computation is limited to a digital paradigm. I believe this dualism is the case because the current CAD/CAM tools designers use are based on a theory of thinking that is modeled as symbol manipulation. Such a viewpoint is known as the symbol information processing model (SIP) which is contrasted with the embodied or situated cognition model. Chapter 3 of this work covers these theories. I saw design computation's roots in information processing models of the mind as a driver of the limitation. If computation is based on the notion of the thinking mind happening in isolation from the body, then it will be very difficult to bring the body back into computational processes. It's already been denigrated as a peripheral process, an output of the mind.

What we need is to expand the definition of computation to include not only the visual but also the physical, the body and its interactive powers. When working with our body, we don't work with symbols, we work with actions and feelings, continuous units of measure. How do we formalize these kinds of units? I believe the answer lies in two areas: in what we formalize and in how we formalize it. With visual computing, Knight and Stiny devised rules and schemas for visualizing shape transformations; however their rules don't specify the kind of actions needed to physically draw the new shape.

The actions of the body and importantly, its interactions with material objects are what need to be formalized. As I showed in my study of playing with blocks, designers physically interact with material in four simple ways: adding, subtracting, modifying, and relocating material. Designers also move themselves around throughout the design process. This is the power of the body; it can move itself and move objects within its reach. This is a quality that computers, in the current way we use them, compress and disregard. It doesn't make a difference if we move around our laptop when working on it. We don't add physical material to a computer screen, nor do we subtract it. The way we work with physical material is fundamentally different than the way we work with digital representations on computers.

A new generation of physical computing tools is on the horizon and my thesis shows ways that designers can harness them. These tools will change the way we interact with the environment through sensing technologies like computer vision and object recognition. Furthermore they will allow us to manipulate objects in the environment in new ways. Our actions become the control mechanism that multiply our actions through robotic manipulators, and extend their reach and speed. The ways we go about doing this is quite simple: addition, subtraction, modification, and relocation. These are the terms through which physical computation tools such as robotic manipulator arms and environmental sensors can be integrated into the design process.

7.2 Contributions to the Field of Design Studies

In my pilot studies I looked at physical manipulation of material objects in the context of closed-ended problems—those with single solutions. These studies helped isolate features that could studied, such as the orientation and configuration of the hand, or the number of actions to transform a set of blocks into a solution state. These features could be measured in terms of time spent to reach the solution. However, much of design activity is not so clear-cut. There is never a single solution and a reaching a solution faster does not necessarily determine its success. Therefore, the problem for the main study became that of developing a method to analyze bodily based activity in an open-ended exploratory process.

In order to understand a kind of process and specifically look at how architects work with physical objects to visually and kinesthetically explore design possibilities, I gave architects, architecture students and non-design students a task to build a model of their dream house. Their design environment was a 4' square site with various contours and elevations, and a set of forty-four different shaped, sized and colored blocks. They were given up to fifteen minutes and were free to use as many or as few blocks in their design. Within this simplified design world, a blocks world, I devised a coding scheme to analyze the material interactions of designers based on three basic actions: picking, manipulating, and placing blocks on the site. With these three actions, four material interactions were observed: adding blocks to a configuration, subtracting blocks from a configuration, modifying blocks within a configuration, and relocating blocks independent of a configuration. Importantly, through this scheme I as able to distinguish the material interactions exhibited by architects from those of novice students and also non-design students.

My main observation is that architects more than student architects seem to materially explore their design in an abstract manner at first, looking for interesting structural relations between the site and configuration of blocks. They also consider other architectural concepts such as negative space, visual connections, and use rules to make connections. Student architects and non-design students are far more functional and pragmatic, placing blocks down to serve as living rooms or kitchens, and other familiar aspects of a house. This difference in concern leads architects to experiment with space differently.

My second observation is that the amount of activity spent experimenting and fishing for new ideas, seems to correlate with design experience. Architects more than novice students and more than non-design students take more time exploring through manipulating and reflecting on the possibilities of each block than on placing a block down and rushing off to get another block. I believe these are the epistemic kinds of actions I was looking for in the hypothesis because often such fishing would take the architects further away from a particular solution but may reveal new block features that help them see more possibilities. As the results showed architects did this in a surprising variety of ways. There were cases in which the novice architecture students were more similar in their interactions to the experienced architects and also some cases in which they were more similar to the non-designers. Although the architects performed fewer Modify interactions overall than the novice architecture students, the architects performed longer sequences of interactions on the blocks suggesting that they think deeper about the impact of each block.

The material based interactions that were observed in this study show that there are indeed designerly ways of using the body. Design thinking is more than visual thinking; it is a physical kind of thinking too, one that can be explained by embodied theories of cognition; one that can be measured with protocol analysis; and one that can be enhanced with physical computational tools. Below I explain these three specific contributions.

7.2.1 An embodied theory of design thinking

The roots of my work grow from theories of embodied cognition in cognitive science. Such theories can be traced back to pragmatist and phenomenological philosophies which reject the dualistic separation of mind and body. To explore the role of the body in cognitive processes of design I have presented theories of embodied cognition. Epistemic action was my starting point for considering action as a driver of design thinking. I demonstrated a connection between reflective action and epistemic action. Making this connection is a valuable contribution to the field of design studies because it opens up the possibility for formalizing embodied action in design thinking. It raises questions as to what designers are looking for in design activity and what kinds of actions help them do this.

With epistemic action we have a way to consider different kinds of bodily actions and different roles for embodied thinking in design activity. Epistemic action is distinguished from pragmatic action in that it does not directly support the completion of a goal, but rather it makes solving complex tasks easier by offloading work to the environment. I believe designers often do not work directly towards completing a specific goal. Rather they work with material to expose and exploit their properties to form spatial relationships and formal ideas. New goals arise in this exploratory process that were not their initially. This was made evident in how architects use blocks to develop new design ideas.

Tools that support epistemic action should help designers in their physical interactive process. By bringing theories of embodied cognition into design computation further research can be conducted on other types of material interactions. An embodied theory of design thinking leads the way for physical computation.

7.2.2 A method for measuring material interaction in design activity

Drawing from protocol analysis methods I have developed a novel coding scheme that captures the body-material interactions in exploratory model making activity. These methods involve coding video recordings of designers in action as the work with physical materials to generate design ideas. The process for deciding what to measure in physical design activity was very challenging. I went through many variations in the coding scheme (e.g., Smithwick and Kirsh, 2015 shows a previous scheme that was developed). In many ways, developing this code was the core work of this study.

I started off very critical of design protocol analysis. I saw it as an extension of the information processing models of cognition as applied in design activity. In hindsight I think protocol analysis methods paved the way to use analytical techniques to understand design as a process. As I discovered, measuring design activity is very challenging. One can only measure what they set out to see, therefore in design protocol analysis it is key what one measures. In applying theories of embodied cognition one looks to the body, however what do we look at? Through my coding scheme I have seen that the primary role of the body in design cognition has to do with how it interacts with material. The coding scheme was not about gesture and it is not about tool interaction, which is the focus of many studies.

My method reveals how material interaction can be designerly, however, I do not yet make claims for the coding scheme's predictive powers. My coding scheme does suggest a way forward to further explore material interaction.

7.2.3 An interactive robotic application

To apply the theories and methods of my study I have demonstrated how a robotic arm can be programmed to physically interact with a designer through material manipulation (Figure 7.1). The designer controls the robot's actions through his own actions with the material. I believe this is a more fruitful way of interaction than through gestural motion control or focusing on interaction with the robotic arm itself. How we control the robotic manipulation of material is the challenge design researchers face moving forward. I have demonstrated control through material interaction of simple flat geometric shapes.

Equipped with vision sensors and object recognition functionality, manipulation tools could explicitly structure interaction sequences within which designers could vary their own action. For example, the robot could pick and place the block and the designer would only do the transformation in-between, or vice-a-versa. Such processes would provide novel interaction constraints giving room for new thoughts.

My vision is to integrate robotic tools into the early exploratory stages of a design process where design ideas are still being formed. The challenge is to computationally support the material-based interactions that we observed in hands-on model making. To do so we need to altogether rethink the way designers use computational tools and processes. Instead of visualizing a design on a computer screen before making it physical, designers ought to be able to work directly with material. As roboticist Rodney Brooks famously said, "The world is its own best model." I interpret this to mean that visualization should happen in real-time as the physical model develops. In other words, the physical model should be its own visualization.

Robotic manipulator arms have the potential to enhance material interaction only if they are equipped with vision and object recognition functionality. What it needs to be able to 'see' is if material has been added to a model or subtracted from it; whether material has been modified within the model, or whether material has been relocated independent of the model. These are the ways we observed designers to interact with materials in model making activity.

The question still remains: how can designers control a robotic manipulator arm without expending more energy in communicating their intent than simply doing the action themselves? What I propose builds on typical CAD-based commands such as creating geometric reflections, copies, arrays, or rotations, but uses material interaction itself as the control interface. For example, if a vision system can see that the designer has added material, the robotic arm can be programmed to copy that particular interaction, or array that interaction, or rotate it. In this sense the designer learns to think through potential robotic actions that duplicate and extend his own.

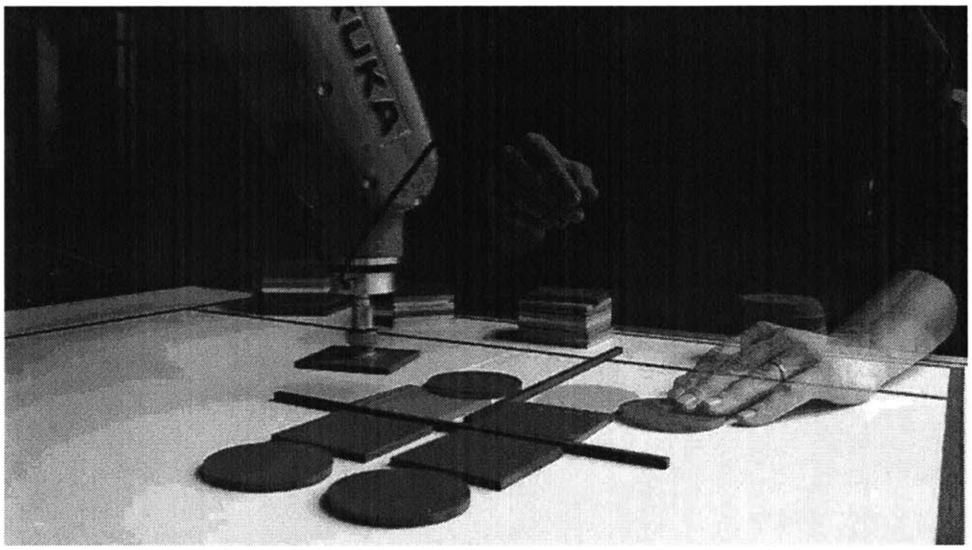


Figure 7.1 A designer can work in real time with a robotic manipulator arm.

To achieve these goals we must re-imagine the designer's work environment. It must consist of a site that is physically accessible to the designer and to a robotic manipulator arm. The manipulator arm must be fitted with an end-effector appropriate to the material. Some material can be rotated and translated, e.g., blocks, but other material can be folded, casted, or cut. A camera must be able to sense the work environment. With 3D material multiple cameras will be needed to support interaction. Lastly, safety is a concern if designers are to physical interact with robotic tools. The ability to sense the designer in the work environment will be needed to avoid collision.

My works presents an alternative vision to the current way designers use computational tools to generate physical designs. In describing the challenge of completing my experimental design task, one of the study participants, an architect and teacher, succinctly captured what it is that designers currently do with digital tools. He said, "I would design the goal [on the computer screen] and then discretize it down to unique units." What he was referring to is the common digital-to-physical workflow in which design work is first completed as a whole on a computer screen. Through digital technology the whole is then sliced and diced into a set of interlocking fabricate-able parts. These parts are then made physical with tools such as laser cutters, 3D printers, or CNC machines. Finally the design is assembled with the parts. But why is this the case?

Why must design thinking be completed on a computer screen prior to making it physical? I believe with physical computing tools design researchers have the opportunity to expand this model of design generation. Instead of thinking of computational tools as output devices for screen-based designs, we can use robotic tools to enhance the actual design generation process through material interaction. We can enhance design thinking through this material interaction.

7.3 Broad Impact of Physical Design Cognition

My work can go beyond traditional design fields however. By expanding the visual nature of design thinking into a physical material interaction we can introduce computational design thinking to many new fields and applications, those which involve the creative physical manipulation of objects, which are numerous. Material based robotic interaction could be integrated into these, including but not necessarily limited the follow examples:

- Cooking
- Construction
- Product packaging
- Physical education
- Gardening & Farming
- Landscaping
- Home repair
- Childhood development

What's important and unique about each of these applications is that they require the creation of an undetermined solution through physical object manipulation. Cooks often work towards known goals, a particular sandwich or pasta, for example; however, they do so with food objects that vary in size, quantity, flavor, etc. Being able to interact in real time and adjust the plan with these objects is crucial for cooking. A robotic manipulator arm in this case could serve as a third hand to aid in bringing food materials together. Construction workers follow plans however they make many choices that are made on the spot with the material in hand in the particular site conditions around them. In packaging products, for example with Amazon orders, workers must bring together various unknown-sized objects and arrange them in creative yet economical ways. Robotic vision systems could help them see possible formations and double their manipulator powers.

Furthermore, learning new physical activities such as soccer and tennis require creative interaction with objects as diverse as racquets and fast moving balls. Training could be enhanced with robotic partners. For example, Kuka Robots, a leading industrial robotic tool manufacturer, recently demonstrated how a robotic arm could be made to play ping-pong with a human opponent. Farming involves working directly with food objects, animals, and farming equipment in ways that change each time the job is done and approached. This is similar in landscaping in which trees and plants must be situated into unique locations and arrangements. Here robotic partners could duplicate actions and extend the reach and strength of an individual. Home repair is another application of material based interactive robotics. Here, professionals and amateurs alike must deal with physical objects without having developed a predetermined plan in advance. This work is more than assembly only. New objects are unpredictable as are their spatial relationships. Being able to deal in real time with these situations is necessary.

7.4 Limitations

One of the biggest limitations of the analytical study in this work is the sample size. With only nine participants, three from each participant group, very little statistical evidence can be gathered to substantiate the claims, therefore reducing its predictive potential. Most the evidence presented in this study is therefore anecdotal, however, I believe suggestive in exciting ways.

Future studies should address data capture limitations in our method. I believe the think aloud method interfered with the participant's natural thought flow. In some cases it seemed the subject was either putting on a performance for the researcher or in other cases the participant was critical of the process of playing with blocks and therefore was not really in the process. Also, I think it may prove fruitful to have two participants work together simultaneously. This could lead to insights into communication strategies for an interactive system.

Another limitation of this study was I did not present any results in terms of process; I only analyzed data as aggregates. As I was developing the coding scheme I did consider the participants' interactions over time, however, no pattern was seen using the schemes. The process and ordering of adding, subtracting, modifying and relocating blocks did not correspond to the participant groups.

Setting up this work in a blocks world scenario did make it easier to analyze discrete actions and also program robotic manipulation of similar actions, but it also limits the application. Designers don't typically work by arranging shapes whether blocks or otherwise; they work with a multitude of materials and variety techniques that help them make physical forms. This limits the study to a toy domain which may not directly apply to typical design practice. Further studies should be conducted on all the variety of materials and manipulations that designers perform. This would go long way towards building up a library of robotic interactions.

7.5 Future Work

With a baseline tool for interacting with a robotic manipulator arm we can study how designers will use the tool and push its limits. I have only begun this by demonstrating a vision for the robotic arm, but its real test will be in how designers engage with it.If designers are to work directly with materials through computational manipulation a wide range of materials will need to studied. How do designers interact with folding paper? How do they work with casting material? What are the designerly ways of working with these materials and how can robotic partners extend and enhance these kinds of interactions?

I believe design researchers should focus beyond human-machine interaction. Rather, the focus should be on human-material interaction. The tool is only there to facilitate this interaction, it is not the primary interaction itself. The tool should fade to the background and leave room for the designer to work directly with material.

Lastly, future work should be conducted on how designers work together. In my study I considered design in a very limited case—a blocks world scenario with designers working in isolation. However, design often happens in groups with people interacting with each other. How do designers think together and how can robotic tools support such collaboration?

7.6 Coda

Physical design cognition spans two fields of research: design studies and cognitive science. On the one hand, design studies seeks to understand the creative design process in the ways designers generate new ideas through sketching, model making, working with tools, and working with others. How can we improve this process and what new tools may support and extend the designer's abilities? On the other hand, cognitive science seeks to understand the nature of the human mind, how we reason about and process the world around us. What are the fundamental workings of the mind and how can we explain the phenomena of seeing and communicating and what it means to be us?

In bringing these fields together in this dissertation I have attempted to create a new body of design knowledge, that which reveals the knowledge of the designer's body in action. We may not literally think with our hands but they give our thinking processes a physical scaffold within which we interact with material objects in the world. With their bodies designers bring materials together, subtract it, modify and relocate it in space. Design as such is a material interaction process that gives form to ideas. These forms are representations whether on paper, a computer screen, or through models. Physical design cognition considers the cognitive aspects of exploratory model making in the ways designer work with materials through their bodies as integral to the creative process.

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Appendix: Experiment Protocols

The following appendix includes participant protocols from the dream house design task. Each subject was video recorded from directly above and their interactions with the blocks were coded in terms of adding, subtracting, modifying, or relocating blocks. These four codes are time-stamped and are color-coded to indicate to following sequences of interactions: manage, assemble, disassemble, explore, test:eject, test:accept, and test:reject. Audio was recorded to capture the participants' thoughts that they voiced aloud during the experiment task.

INTERACTION SEQUENCES KEY
MANAGE
ASSEMBLE
DISASSEMBLE
EXPLORE
TEST:EJECT
TEST:ACCEPT
TEST:REJECT

Participant RM, Architect

4:10	**Total interaction time**
2:48	Relocate
2:49	Relocate
2:51	Relocate
2:52	Relocate
2:55	Relocate
2:56	Relocate
2:58	Add
3:05	RM: *I could tell you what I like about these figures... I like that these create an 'outdoor/indoor'... a kind of exterior spatial definition and an interior spatial definition... it's super strong... and you don't have to do much to let them do that... which is nice.*
3:07	relocate
3:24	Relocate
3:27	Modify.6
3:33	Add
3:34	Modify.8
03:40	RM: *I should keep playing around... It would be nice to create an exterior figure that is defined as the interior.*
3:44	Modify.2
3:46	Modify.1
3:47	Modify.4
3:51	Modify.1
3:52	Subtract
3:53	Modify.1
3:54	Add
3:55	Modify.2
3:56	Subtract
3:58	Relocate-Inspect.1
3:59	Modify/modify.2
4:01	Add
4:02	Modify.12
4:19	Modify.11
4:31	Subtract
4:35	Modify.3
4:39	Modify.1
4:40	Add
4:45	Add
4:51	Modify.4
4:55	Subtract
4:56	Add
4:57	Modify.8
5:07	Modify.15
5:22	Subtract
5:23	Relocate-Inspect.2
5:25	Add
5:26	Modify.9
5:40	Add
5:41	Modify.6
5:48	Add
5:49	Modify.8
6:02	Add
7:00	RM: *I didn't intermingle the blocks because I like the way the others (the red ones) fit together. It's more controlled for me. I still really like the ability to make a single figure that has a lot of interior/exterior spaces. I can't go through it and say what's my bedroom, what's my living room... like how it all works... as a plain figure I like it and can imagine it occupied in many ways.*
	DS: *if you were to describe your strategy to a freshman or high school student... how would you describe what you did?*
	RM: *in a really robotic way... it's just aligning equal sides by equal sides in a way that allows them to lean together or pull apart which allows passage through it. The blocks are pretty prescriptive... but I like being able to create areas that open up... areas of shadow areas that aren't shaded, they're attractive cantilevers. I don't know that I can explain it as a methodology specific to a house... but more as a methodology for a composition. Things like orientation and site are tricky. I like that everything is equal sized. They could each be individual rooms. There are moments when they open up to each other to become a larger room. Or you could subdivide them further within each cell to be multiple rooms. I like the ambiguity of some being exterior wall or an exterior court with walls around... they're not a clear prescriptive enclosure which I lik*

Participant SK, Architect

12:11 Total interaction time

0:58	*SK: "What scale are we looking at here?"*
1:00	*DS: "up to you"*
1:05	*SK: "you have to assume that the smallest module is a living space...so...[this block] is a bedroom...but that would mean an enormous dream house"*
1:20	Relocate-Inspect/Relocate-Inspect.18
1:40	Add
1:41	Modify.13
1:54	Add
1:55	Modify.10
2:05	*SK: "Using the blocks, I am creating face-matching walls"*
2:06	Add
2:07	Modify.11
2:18	Add
2:19	Modify.8
2:27	Add-Inspect.2
2:31	Modify.3
2:35	Subtract
2:38	Relocate
2:41	Add
2:42	Modify.6
2:45	*SK: "I would normally do a skip thing...2 up 1 down...but there's no green one"*
2:48	Subtract
2:49	Add
2:50	Modify.9
3:00	Relocate
3:02	Relocate
3:03	Add
3:04	Modify.10
3:15	Add
3:16	Modify.11
3:32	Relocate
3:36	Relocate-Inspect.2
3:42	Relocate
3:45	*SK: "I am going to shift the subassembly to where I would like it to be."*
3:45	Relocate/relocate
3:47	Relocate
3:49	Modify/Modify.12
4:03	Relocate-Inspect.7
4:13	Add/Add
4:18	Relocate
4:19	Modify.3
4:29	Modify.2
4:33	Modify.12
4:35	*DS: "can you explain your process right now as if to someone who has no idea what designers do?"*
4:52	Relocate-Inspect.7
5:05	*SK: "I'm looking for...what I'm hoping this will be is some kind of dividing wall...or on this side I want to have an elevated mass...held up by three [blocks]...because I want the idea of danger to be present."*
5:17	Modify.3
5:23	Add
5:24	Modify.2
5:26	Subtract
5:35	Add-Inspect.1
5:45	*SK: "so here is a mysterious figure rising out of the ground...supported tenuously"*
5:45	Modify.1
5:47	Modify.1
5:48	Modify.1
5:55	*SK: "I'm going to say that's the kitchen...why?..I don't know...but I like the idea of a central thing around which the home will be"*
5:58	Relocate-Inspect.18
6:16	Relocate
6:18	Relocate
6:22	Relocate
6:27	Add
6:28	Modify.3
6:32	Modify.3
6:35	Subtract
6:37	Add
6:38	Modify.3
6:41	Subtract
6:42	Add-Inspect.1
6:48	Subtract
6:49	Relocate
6:51	Relocate-Inspect.3
6:57	Relocate
6:59	Relocate
7:05	Add
7:06	Modify.6
7:13	Add
7:15	Modify
7:19	Subtract
7:20	Add
7:21	Modify.3
7:25	Add

7:26 Modify.8
7:41 Add
7:42 Modify.7
7:45 *SK: "What I want to do with this one [the new configuration]...since there is no long linear piece...what I can say...is that I'm creating a visual connection between these two volumes.*
7:59 Subtract/Modify.2
8:01 Modify.1
8:02 Subtract
8:03 Add
8:04 Modify.2
8:05 *SK "I wish this sat a little nicer [referring to how new configuration sits on site model]"*
8:06 Add
8:11 Modify.2
8:20 relocate-Inspect/relocate-inspect.7
8:28 Add
8:29 Modify.4
8:33 Subtract
8:35 Relocate-Inspect/Relocate-Inspect.10
8:47 Relocate-Inspect/Relocate-Inspect.10
8:59 Add-Inspect.1
9:05 Add
9:06 Modify.9
9:21 Relocate-Inspect.12
9:35 Modify/Modify.14
9:52 Modify/Modify.1
9:54 Relocate-Inspect.2
9:57 Add
9:58 Modify.17
10:16 Subtract
10:16 *SK: "That would have been cool...that's a shame...that would have been apex to apex"*
10:17 Modify.5
10:26 Relocate
10:30 Relocate
10:32 Relocate
10:39 Subtract
10:45 Modify.38
11:23 Add
11:29 Modify.3
11:35 Remove
11:37 Modify.11
12:25 *DS: "How do you know how to place the blocks next to each other?"*
12:30 *SK: "I'm thinking 3 compartments that are double height"*
13:10 *SK: "That's it. 3 characters – my wife, me, and my kids [pointing to the 3 configurations]...so this is no longer a kitchen"*

Participant BC, Architect

10:05 Total interaction time

1:07	Relocate
1:09	Relocate
1:13	Relocate
1:14	Relocate-Inspect.2
1:17	Relocate-Inspect.2
1:19	Relocate
1:22	Add
1:23	Modify.4
1:30	Modify.2
1:32	Modify.2
1:35	Modify.1
1:36	Add
1:37	Modify.3
1:42	Subtract
1:52	Add
1:53	Modify.2
1:55	Add
1:56	Modify.6
2:00	*BC: I'm going to start by setting up a Pilotis - it's like a frame to lift things off the ground. If I'm working with a fixed set of units I'm going to say this is going to be a Modern house, not digital. So I'm going to use le Courbuseir's process.*
2:04	Relocate
2:05	Relocate
2:06	Relocate
2:14	Add
2:16	Modify.4
2:22	Add
2:28	Add-Inspect.1
2:30	Modify.4
2:35	*BC: I like the relationship with this edge (pointing to the site model) because it's pulling down even further. I would consider over there (pointing to another spot on the site) but it's not flat, so I like this area. It's possible I may want to shift the whole thing (the configuration) up that way (away from his body)*
2:38	Relocate
2:44	Add
2:59	Modify/Modify.11
3:14	Modify/Modify.2
3:16	Modify.2
3:29	Modify.7
3:30	*DS: With these blocks...these 'kit of parts'...you said that your design would be a Modern one and not digital'...what did you mean by that?*
3:45	*BC: I would never use a kit of parts in my own work. I would design the goal and then discretize it down to unique units. The kit of parts is a modern way of thinking about how can you mass produce elements that you then re-configure together to produce different solutions. But the solutions you can produce are limited. So...this is out of my comfort zone to use fixed parts.*
3:48	Relocate/relocate
4:18	Relocate
4:22	Add
4:24	Modify.10
4:36	Add
4:42	Modify.1
4:44	Relocate-Inspect.2
4:45	*BC: I have many pre-conceived notions of what is right and what is wrong. Like...I would never have mandated for myself that I use a kit of parts.*
4:46	Modify/Hold.1
4:52	Subtract
4:55	*DS: So this is challenging to you?*
4:56	Subtract
5:00	*BC: yeah...this brings me back to undergrad*
5:10	*DS: is it challenging in a similar way to how the rotation and flipping tasks were challenging?*
5:00	*BC: no...because those have a solution. For here, I have to invent a problem for myself to resolve. I usually do this through uniquity...through unique units. I would like to scale these blocks so they align. But I can't do that because I have a fixed set of parts. So I'm just going to have a gap in my building.*
5:37	Add
5:39	Modify.6
5:46	Add
6:05	Add
6:08	Modify.1
6:10	Modify.1

6:18 Add
6:32 Add
6:44 Subtract
6:48 Relocate-Inspect.5
6:54 Relocate
6:57 Relocate
6:58 *BC: One thing I'm trying to do is make things flow.*
9:50 *BC: I would say I remove the idea of bedrooms, bathrooms, etc. and all those preconceived notions of what you do in a house because that's not what you do in a house...you don't bedroom, you don't kitchen, etc. You enter, you inhabit, you relax...so I'm trying to think of producing a space that would allow you to move through it in different ways. Openness and enclosure...so i'm thinking about the sequence...and of course we can't do a bedroom or bath with these blocks, but what we can do is define space. So my idea is that when people come to the house from this way, they see this edge...so when you enter, you go under and it's very dark. I'm going to say this is done. This block is moving in this direction...when you come under you experience this that way, but then you're pushed that way. Now you're at a level that you can look at this (point to the site model wall) and then by the time you get up here you're back on something that looks out that way. So you have open, then condensed with something overtop, then focused looking (gesturing now with hands by his eyes) out that way, then up tiny focus out that way then just totally open at the top.*

Participant MR, Novice architecture student

12:15 **Total interaction time**

1:27	Relocate-inspect.5
1:33	Relocate-inspect.7
1:40	Relocate-inspect.2
1:42	Relocate
1:44	Relocate-inspect.3
1:48	Relocate-inspect.3
1:51	Relocate-inspect.2
1:55	Relocate
1:58	Relocate
2:01	Relocate
2:02	Relocate
2:04	Relocate
2:11	Relocate
2:13	Relocate
2:15	Relocate
2:27	Relocate-inspect.3
2:30	Relocate
2:32	Relocate
2:41	Relocate-Inspect.1
2:46	Relocate
2:52	Add/Add
2:53	Modify.3
2:56	Modify/Modify.12
3:09	Add
3:10	Modify.7
3:18	Modify.8
3:31	Relocate-Inspect.1
3:32	Relocate-Inspect.1/Add
3:33	Relocate-Inspect.19/Modify.19
3:45	*DS: If you were to explain what you were doing to a relative who knows nothing about design, what would you say you're thinking about right now?*
3:54	Add
3:58	Relocate-Inspect.1
4:05	Add
4:09	Modify.2
4:11	Modify.1
04:10	*MR: I'm using this [area] as the entrance...and I'm going to use these [green blocks] as the grass and flowers...and these [the wireframe blocks] will be windows. These [the blue blocks] look heavier so those will be the big walls...like the frame of the house.*
4:21	Relocate-Inspect.1
4:28	Relocate
4:34	Relocate-Inspect.1
4:35	Relocate-Inspect.1
4:53	Add
4:54	Modify.5
4:59	Add
5:00	Modify.5
5:06	Add
5:07	Modify.6
5:13	Modify.1
5:15	Add
5:16	Modify.16
5:32	Subtract
5:33	Add
5:34	Modify.15
5:57	Add
5:58	Modify.5
6:05	Add
6:07	Modify.5
6:13	Subtract
6:16	Relocate-Inspect.1
6:26	Relocate-Inspect/Relocate-Inspect.1
6:31	Add
6:32	Modify.8
6:42	Add
6:43	Modify.4
6:47	Add
6:48	Modify.5
6:54	Modify.2
6:57	Add
6:58	Modify.16
7:15	Modify.1
7:16	Relocate
7:22	Relocate
7:30	Add
7:32	Modify.2
7:35	Add
7:37	Add
7:39	Modify.1
7:40	Add
7:41	Modify.6
7:52	Add
7:56	Add/Add
8:02	Add
8:04	Add
8:07	Modify.2
08:10	*MR: These are my flowers and a fountain now too*
08:15	*MR: and I have to close the house...so I could have...*
8:20	Subtract
8:26	Modify.4

8:30	**Modify/Modify.7**
8:38	**Relocate**
8:44	Add
8:45	Modify.4
8:52	**Relocate-Inspect.1**
8:58	**Add**
8:59	**Modify.1**
9:03	**Add**
9:04	**Modify.6**
9:09	**Modify.6**
9:15	Modify.7
9:23	Subtract
9:24	**Relocate-inspect.1**
9:25	**Add.1**
9:28	Add
9:29	Modify.1
9:30	**Subtract-Inspect.1**
9:30	**Modify/Modify.4**
9:34	Add
9:35	Modify.4
9:40	**Add.1**
9:41	**Modfiy.3**
9:44	**Modify.5/Hold.5**
9:49	**Modify.2**
9:51	Add.1
9:52	Modify.4
9:58	**Relocate.1**
10:00	**Add**
10:01	Add
10:02	Modify.7
10:09	**Modify-Inspect.1**
10:10	**Modify.4**
10:16	**Add**
10:18	Add
10:19	Modify.6
10:25	Add
10:26	Modify/Modify.13
10:42	**Subtract**
10:47	Add
10:49	Modify.2
10:52	**Modify.1**
10:54	**Subtract**
10:56	Modify-Inspect/Modify-inspect.14
11:10	Modify.2
11:10	***MR: It'd be cool if these [blocks that she picked up] were mirrors of each other***
11:13	Modify.3
11:16	Modify.3
11:19	Modify.7
11:29	Modify.5
11:35	Modify/Modify-hold.7
11:43	Modify.3
11:47	Modify/Modify.hold.7
11:50	*DS: I notice you are moving your head down near the blocks...what is that for?*
12:00	*MR: I want the entrance to be symmetric...from this angle...*

Participant JG, Novice architecture student

10:00 Total interaction time

3:14	Relocate-Inspect/relocate-inspect.7
3:21	Relocate
3:23	Relocate.4
3:28	Modify/modify.9
3:37	Add
3:38	Modify.13
3:53	Subtract
3:53	Add
3:54	Subtract/Modify
3:55	Modify/Modify.5
4:03	Add/add
4:06	Add/Relocate
4:07	Modify/Modify.2
4:09	Modify/Modify
4:11	Modify/Modify.2
4:12	*JG: How do I fit these together?*
4:14	Modify.1
4:16	Modify-inspect/Modify-inspect.3
4:21	Add
4:22	Modify/Modify.2
4:24	Add
4:25	Modify/Modify.7
4:32	*JG: I would like...because they're parallelograms...if they did fit together and I could make a hexagon that'd be cool.*
4:36	Modify/Modify.5
4:43	Modify/Modify.5
4:49	Modify/Modify.2
4:51	Modify/Modify.1
4:52	Modify/Modify.1
4:53	Add
4:54	Modify.1
4:55	Modify/Modify.2
4:58	Modify/Modify.1
5:00	Modify/Modify.1
5:02	Modify/Modify.1
5:04	Subtract
5:05	Subtract
5:06	Add
05:07	*JG: Ok...I'm going to line this up*
5:07	Modify.1
5:08	Relocate
5:09	Relocate
5:11	Modify/Modify.1
5:12	Add
5:14	Modify.5
5:20	Add
5:21	Modify.7
05:22	*DS: if you were to try and explain what you do as a designer to a relative or friend...how would you describe what you're doing here?*
5:29	Relocate
5:30	Add
5:31	Modify.5
5:37	Modify/Modify.1
5:38	Modify/Modify.10
5:45	*JG: I'd say right now, even I don't know what I'm doing...that's kind of part of design*
5:49	Add/add
5:50	Modify/Modify.4
5:54	Modify/Modify.1
5:55	Relocate/Relocate
5:58	add
6:00	Modify.2
6:02	Subtract
6:04	Relocate/relocate
06:05	*JG: I think often times I start designing something...like coming in here I have no idea what I'm doing...so...I know I want to work off of this wall in some way...so I'm just starting and figuring out what I'm doing...and that'll hopefully will come naturally.*
6:08	Relocate-inspect.5
6:13	Add
6:14	Add
6:15	Modify.5
6:20	Modify/Modify.2
6:21	Subtract-Inspect.7
6:31	Relocate-Inspect.2
6:33	Modify.2
6:36	Add
6:39	Add
6:41	Modify.2
6:43	Add
6:45	Modify/Modify.2
6:48	Add
6:49	Modify.4
6:53	Subtract
6:54	Add
6:55	Modify.8
7:06	Modify/modify.12
7:21	Relocate
7:25	Add

7:26	Subtract
7:26	Add-Inspect.4
7:30	Modify.2
7:33	Relocate
07:36	*JG: I see this [area of the site] as a more natural landscape...maybe this is a street...an urban flat space. Maybe my house will have a street in front and a park or forested more natural area that I would really value. So I'm trying to connect the 2...maybe I could knock a hole in the wall or maybe just go over it.*
8:02	Add
8:06	Relocate
8:15	Relocate
8:18	Add
8:20	Modify.1
8:22	Subtract
8:23	Modify/Modify.5
8:28	Modify/Subtract-Inspect.1
8:29	Modify/Add
8:31	Add
8:33	Modify-Inspect.1
8:35	Subtract
8:36	Add
8:37	Modify.2
8:39	Modify-Inspect/Modify-Inspect.20
9:02	add
9:05	Modify.5
9:11	Add
9:13	Add
9:15	Modify.3
9:19	Modify
9:20	Subtract
9:21	add
9:22	Modify.2
09:25	*JG: this is more sturdy*
9:25	Relocate
9:27	Relocate-Inspect.1
9:31	Relocate-Inspect.2
9:39	Modify.5
9:44	Modify/Modify.4
9:48	*JG: There we go*
9:49	Modify/Modify.2
9:52	Modify.3
9:57	add
9:58	Modify.4
10:03	Subtract
10:04	*JG: These are hard to stack*
10:05	add
10:07	Modify.8
10:17	Add
10:18	Modify.3
10:22	Modify.8
10:31	Modify.8
10:41	Modify.4
10:45	Modify.7
10:59	Modify.1
11:05	add
11:15	Relocate
11:20	Relocate-Inspect.4
11:25	Relocate-inspect.2
11:20	*DS: Before you started...where you planning out what you wanted to do?*
11:25	*JG: no...I looked at the blocks and thought..oh this is cool...and I thought...oh these are like windows kind of...so I'm definitely using these [the wireframe blocks] for spaces that I would like to be more open. I realized especially when I dealing with shapes I'm not familiar with...if something's in 2d I can imagine it in my mind...but if its 3d I don't know what can of problems I going to have so I feel like I can 't prepare for it...I just have to do it.*
12:40	*DS: so what kind of problems are you dealing with now?*
12:48	*JG: these shapes are very frustrating...because it looks like it will line up and then it won't line up. So one of the things I did think of was...oh, diamonds...maybe I can make a hexagon...but that didn't line up.* *Also...these are hard to stack on the lower ones because of the holes in the middle. That's another challenge.*
13:50	*DS: are you imagining...here's this room, here's that room...or is that not really what youre thinking about?* *JG: I'm even more vague than that...I'm imagining a fluid...the house to be an intermediate between the normal city area vs the natural landscape back here. My main goal was in bridging that gap in getting over the wall...and depending on what kind of wall this is...if I can have a house that goes through it or maybe the house goes up and over...I knew that I wanted it really open, especially on this side...I considered this a more open room, and this potentially more closed and if there are neighbors maybe that's good.*

Participant JC, Novice architecture student

9:40 **Total interaction time**

1:22	Relocate
1:24	Relocate-inspect.2/Relocate
1:25	*JC: I feel like this is easier for people who have a dream house in mind... and I don't.*
1:29	Relocate-inspect.2
1:31	relocate/relocate
1:34	relocate
1:36	relocate
1:37	relocate
1:38	relocate
1:40	relocate
1:41	relocate/relocate
1:43	add/add
1:44	modify/modify.12
1:59	Add
2:00	*JC: what's interesting about these is that they're all parallelograms so nothing will be a boring rectangular form. So maybe they don't need to be flush.*
2:01	Modify/modify.7
2:09	Modify.2
2:11	Relocate
2:13	Modify.2
2:15	*JC: I like trees... I also like courtyards*
2:16	Relocate
2:18	Relocate
2:20	Relocate
2:21	Relocate
2:23	Relocate
2:24	Relocate
2:25	Modify.2
2:27	relocate
2:29	Relocate-inspect.4
2:33	Relocate-inspect.7
2:44	relocate
2:46	Add
2:48	relocate
2:50	Modify.1
2:52	Relocate
2:54	Relocate
2:55	Add
2:58	subtract
2:59	Modify.11
3:11	Add
3:12	Modify.15
03:15	*JC: Courtyards are like a design thing that never really took off in the western world*
3:27	Add
3:28	Modify.4
3:35	Modify.6
3:44	relocate
3:50	relocate/relocate
3:54	Add
3:55	Modify.2
3:56	subtract
3:57	Add
3:58	Modify.3
4:02	Subtract
4:03	Modify.5
4:08	Subtract
4:11	Add
4:12	Add
4:13	Subtract
4:14	Subtract
4:15	relocate
4:17	Add
4:18	Modify.8
4:26	Modify-inspect/Modify-inspect.12
4:39	Subtract
4:40	Add
4:41	Modify/Modify.8
4:50	Relocate
4:56	Add
4:57	Modify/Modify.2
4:59	Subtract
5:01	Modify.4
5:06	Add
5:08	Modify.1
5:09	Modify.3
5:13	Modify-inspect/modify-inspect.9
5:23	Relocate-inspect.4
5:30	Add
5:31	Modify.8
5:41	Add
5:42	Modify.5
5:49	Add
5:50	Modify.1
5:52	Subtract
5:55	relocate-inspect.2
5:58	Add
6:03	Add
6:07	Add

06:09 *DS: How would you describe your strategy right now as an architecture student to a relative who has no idea what designers do?*
6:12 Modify.1
6:14 relocate
6:16 relocate
6:18 Add
6:19 Modify.4
06:20 *JC: to an aunt or uncle you want to sound legitimate...not just pushing and pulling things around until it looks reasonable or follows some logic. So...to an aunt or uncle...it's like I design things by envisioning them creatively in my mind and then executing them in a process of 'something' 'something'.*
6:23 relocate
6:28 Add
6:29 Modify.3
6:35 Add
6:39 Modify.1
6:46 relocate
6:48 relocate
06:50 *DS: How are you using these blocks to help you think through this design task?*
6:50 Add
6:52 Modify.11
7:07 add
07:10 *JC: Definitely some of the blocks because of the way they suggest certain shapes and certain spaces...like the hollow wire frame ones remind me of things that are opening upwards, while these more solid ones (the blue ones) are like...I wouldn't say walls because I'm not thinking about walls right now which is kind of weird...but more things that could suggest space delineators...also I was just making bushes (the green blocks). I also like color. I think here was kind of an entry way because it was grandiose...and it's red, red is important.*
08:45 *JC: because these are such abstract and odd forms you can say that they're whatever. Right now I'm building rooms back off the courtyard...so these are like rooms but also like walls. So it's more that this is a nebulous shape of a building that contains spaces inside it that you can't really explore with these blocks.*
Normally in a design process you think about it for a long time and then you come up with a logic so that it's more coherent for a design review.
So now I'm putting things together and thinking about them at the same time...
I've now discovered that I should work on it from several points of view at once. I've noticed from this view it's built up like this...so I guess my dream house is courtyards and towers and stuff.

Participant CY, Non-design student

3:30	**Total interaction time**
01:05	*CY: This will be just the structure of the building, right? Not the stuff inside?*
1:06	relocate
1:08	relocate-inspect/relocate-inspect.16
01:10	*DS: Up to you...you tell me how those things are in your design*
1:23	Add
1:25	relocate
1:27	relocate
1:28	Modify-Inspect/Modify-Inspect.5
1:33	Subtract
1:34	Add-inspect/Add-inspect.6
1:41	Add
1:44	Modify.4
1:50	Modify.10
2:00	Add
2:01	Subtract
2:02	Add
2:04	Modify.14
2:19	Add/add
2:20	Modify/modify.2
2:22	Subtract/subtract
2:23	Add
2:24	Subtract
2:25	Add
2:31	Add
2:33	Modify.1
2:38	Relocate-inspect.5
2:47	relocate
2:49	Subtract
2:51	Add
2:54	Add
2:55	Modify.7
3:04	Add
3:05	Modify.14
3:19	Modify/Modify.3
3:24	Add
3:27	Add
3:38	Add
3:38	relocate
3:40	relocate
3:42	relocate
3:43	Add
3:50	Add
3:51	Modify. 4
4:03	Add
4:11	Relocate/relocate
4:27	Relocate
4:35	Add
04:45	*CY: I like rock climbing so I'd like to have something I can climb. That's what that is.*
05:10	*DS: How are the different blocks helping you design your rock wall house?*
05:25	*CY: The first time I used only the outsides...the smooth side...and I thought that would suck [for rock climbing] so I wanted there to be holds everywhere. And obviously because it's my dream house each one of these is a room.*

Participant FT, Non-design student

10:21	**Total interaction time**
1:03	Relocate-Inspect.16
1:42	Relocate-Inspect/relocate-inspect.8
1:55	Add
1:56	Modify.15
2:16	relocate-inspect.3
2:22	relocate-inspect/relocate-inspect.12
2:47	relocate
2:50	relocate-inspect.9
3:00	relocate-inspect.11
03:04	*FT: I'm curious what people use this [block] for...*
03:05	*DS: it's been used for everyth*
3:13	relocate-inspect.7
03:15	*FT: so I'm now trying to think of what landscape I want this to be... the setting...for example... I thought these were wave-like... but maybe these are... it's interesting*
3:49	Add/add
3:51	Add
3:57	Add
3:59	Subtract
4:05	Relocate-inspect/relocate-inspect.7
4:13	relocate
4:16	relocate
4:18	relocate-inspect/relocate-inspect.9
4:32	Add
4:34	Relocate-inspect.6
4:44	Add-inspect.4
4:51	relocate-inspect.5
5:01	relocate-inspect.4
5:09	relocate-inspect.5
5:15	relocate
5:17	relocate
5:19	relocate-inspect.5
5:31	relocate
5:32	Add
5:33	Modify/modify.6
5:40	Modify/modify.10
5:54	Add
5:55	Modify.9
6:06	Add
6:07	Modify.8
6:17	relocate-inspect.14
6:28	*FT: I'm trying to build a way for the design to interact with the landscape... I sort of made a miscalculation... this [set of blocks] was supposed to be some way for people to get up here, but then I realized that this [block] is the scale size of a room...*
06:43	*DS: What scale?*
06:44	*FT: I'm thinking of this [block] as a room... so you can't really step on these*
6:47	Modify.1
06:51	*FT: so right now I'm imagining this [open area on the site] as the ocean and I'm orienting the rooms so that you can see out into the landscape... so these are 2 living spaces like lounges or a dining room and these can be like bedrooms*
7:12	relocate-inspect.16
7:30	*FT: I've oriented these so that both have the diagonal hole going that way... that would feel pretty interesting if all your walls were slanting in*
7:33	relocate
7:37	relocate-inspect.3
7:41	relocate-inspect.1
7:43	relocate-inspect.3
7:51	relocate-inspect.1
7:53	Modify.2
7:57	Relocate
7:58	Modify.4
08:05	*FT: maybe it's connected with a tunnel*
8:05	Add
8:09	Subtract
8:10	Add
8:11	Modify.2
8:13	subtract
8:15	Relocate
8:18	Add
8:19	Modify.3
8:27	Add
8:28	subtract
8:30	Add
8:31	Modify.9
8:41	Add
8:42	Modify.9
8:53	Modify.2
9:05	Modify.3
9:08	Modify.1
9:09	Modify.2
9:11	Modify.4

9:13	***FT: I'm making this tunnel to connect it... it didn't line up here but I think it's actually kind of cool... it lets the sunlight in there.***
9:22	**Modify.2**
9:29	Add
9:30	Modify.5
9:37	**Relocate-inspect.2**
9:41	**relocate**
9:44	Add
9:45	modify.2
9:52	**relocate-inspect.5**
10:04	Add
10:05	Modify.5
10:10	**subtract**
10:24	add
10:26	Modify.6
10:36	Add
10:37	Modify.6
10:43	**Modify.6**
10:50	Add
10:51	Modify.2
10:54	**Modify.2**
11:06	**Modify.15**
11:23	Add
11:24	Modify.2
11:32	***FT: they're not aligned, which started out by accident, but I think it would be kind of cool as an idea, if not for my actual house if you had to navigate through this convoluted maze of rooms in order to get to this beautiful view... it might not be the most efficient... but if you were visiting this house for the first time as an experience it'd be cool if all these rooms were in weird ways rather than just having a tunnel that goes straight through.***

Participant RW, Non-design student

8:43 **Total interaction time**

1:05	Relocate
1:06	relocate
1:07	relocate/relocate
1:09	relocate/relocate
1:11	relocate-inspect/relocate-inspect.3
1:15	relocate/relocate
1:17	relocate
1:20	relocate
1:29	relocate
1:30	relocate
1:44	relocate
1:49	relocate
1:50	*RW: I'm just looking at the different kinds of pieces I have right now...and maybe I'll assign each piece a different role in the house.*
1:51	relocate
1:51	relocate-inspect/relocate-inspect.9
2:02	add
2:07	add-inspect.8
2:12	*RW: these aren't necessarily walls, but maybe just open space*
2:21	subtract
2:22	add-inspect.2
2:25	add
2:31	modify.2
2:36	relocate
2:38	relocate
2:40	modify-inspect.7
2:48	subtract
2:55	Add
2:59	*RW: is there anything to be said about the surroundings?*
3:06	*DS: you tell me...up to you*
3:15	Add
3:16	Modify.2
3:21	Add
3:22	Add
3:27	Add
3:35	Add
3:39	Modify.2
3:41	Modify.1
3:45	RW: *it'd be kind of cool to have a wall of windows along the side of the house...maybe the south facing side where there's a lot of sun.*
3:46	relocate
3:51	relocate-inspect.8
4:01	relocate
4:04	relocate
4:11	relocate-inspect.2
4:17	relocate-inspect.3
4:23	Modify.2
4:24	relocate
4:25	Relocate
4:27	Add-inspect.7
4:38	Modify.1
4:40	relocate
4:48	relocate
4:49	relocate-inspect.2
4:50	*RW: maybe I'll use these as passage ways...hallways*
4:53	relocate
4:55	relocate
5:01	relocate-inspect.3
5:04	relocate
5:06	Add
5:10	Modify.2
5:12	subtract
5:14	relocate
5:16	Add
5:17	Modify.3
5:20	relocate
5:22	subtract
5:28	add
5:30	Modify.2
5:33	Add
5:40	Modify.1
5:43	Add-inspect.10
5:55	modify.3
6:01	Add-inspect/add-inspect.6
6:08	modify.3
6:13	modify.1
6:14	relocate-inspect.3
6:18	relocate-inspect.4
6:26	relocate-inspect.5
6:32	relocate-inspect.3
6:50	relocate
7:01	Add
7:09	add
7:18	add
7:20	relocate-inspect.2
7:26	relocate
7:28	Add
7:32	Add-inspect.12
7:47	Add
7:51	subtract/subtract
7:53	relocate-inspect.5
7:58	Add-inspect/add-inspect.6
8:10	subtract

8:32	**relocate**
8:38	**relocate-inspect.4**
8:43	**relocate-inspect.2**
8:46	add
8:47	Modify.8
8:57	Add
9:01	Add
9:07	Add-inspect.4
9:15	**Add-inspect.5**
9:22	**relocate**
9:23	**Modify.1**
9:27	Add
9:29	Modify.2
9:36	Add
9:37	Modify.6
9:58	***RW: this is a wide open living room, here's an open hallway on the side of the building... the little blocks I'm treating as hallways and maybe stairs, this is the kitchen, here is a studio... there's bedrooms on the second floor.***