Title

Creative Interaction with Blocks and Robots

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Abstract

In order to creatively interact with robots we need to understand how creative thinkers work with objects to explore new ideas physically. Our approach involves comparing the model-making strategies of architects with students to expose the creative extras architects bring to working with physical models. To study this we coded students and architects performing a design task. Architects differed from students along three dimensions. First, architects were more selective; 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 re-orientations: they position a block one way to see its relations to its neighbors; they reposition it another way to see how that changes how things look and feel. These findings suggest that designers interact with the material more effectively than students. This embodied know-how is something next generation robots can support and possibly enhance.

Keywords: design thinking; interaction; robotics

Introduction

Much of what has been said of design thinking is about manual sketching activity: it is the means by which designers have ‘reflective conversations’ with their design (Schon, 1992); it is how designers ‘see as’ and ‘see that’ (Goldschmidt, 1991); 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 thinking initially takes form as exploratory sketching activity.

However, sketching is not always necessary in design activity (Bilda, Gero, and Purcell, 2006) and it is not the only means of exploring a design manually. Architects also make physical models, including: sketch models, diagram models, concept models, massing models, presentation models, and more (Mills, 2011).

Unlike sketching, which involves marking a two-dimensional paper surface, physical model making takes place in three dimensional space and involves different forms of material interaction. For instance, different modeling materials afford different actions: chipboard can be layered, paper can be folded, wood can be milled, concrete can be cast, and so forth.

If sketching is thought of as visual design thinking (Goldschmidt, 1994), model making, with its emphasis on building, assembly and manipulation, ought to be considered physical design thinking – a more tangible, interactionist way of exploring designs.

Framing certain forms of action as enactive thinking is central to theories of embodied and situated cognition (Anderson, 2003). Gesture can facilitate thinking in calculation (Martin, 2005) and problem solving (Goldin-Meadow and Beilock (2010). Body movement enables dancers to probe movement structures in ways inaccessible through observation alone (Kirsh, 2011).

Our objective here is to extend the notion of design thinking to physical model making. What sketching is to visual thinking model making is to physical thinking. To explore this idea we created a simple design world – a blocks world – where model making is abstracted to picking, manipulating, and placing blocks in a configuration on a site. We devise a simple coding scheme that tracks the key material interactions over time. By video recording the design sessions of designers and non-designers we are able to compare their interactions and by using the method of voice aloud protocol analysis we can relate these to what is said during activity. Assuming designers do behave differently than non-designers, our central concern is to elucidate a framework that will reveal these differences and explain them.

Our ultimate motivation is to provide a theoretical and empirical foundation for interactive robotic design tools that enhance the material-based nature of exploratory model making activity. As digital technologies become more physical – more interactive and integrated into the design environment – theories of physical design thinking are needed to guide the development of supportive tools.

Background: Coding Design Activity

Protocol analysis methods have often been used to codify actions in design activity and correlate them with a designer’s thoughts.

Coding schemes are used to define and count discrete actions within design activity. Many studies are based on Suwa and Tversky’s 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. Suwa et al (1998) adapted these categories to correspond to the flow of cognitive processes involved in human cognition: distinguishing physical, perceptual, functional, and 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 setting up goals and making value judgments based on domain knowledge.

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. They observed that in terms of the overall number of actions performed during sketching, an expert is more active and productive than a novice. Furthermore, experts increased their rate of action over time while novices decreased theirs. They found that an expert is three times more selective in how many actions they deal with at once, suggesting their design process is more controlled and efficient.

In the current work, we are interested particularly in how physical action in model making drives design thinking and in what ways this may differ between experts and novices. Looking more closely at the kinds of physical actions defined by Suwa et al (1998), however, we find their action types ill-suited for describing material interactions in model making. They distinguish these seven:

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

In physical model making 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. The actions possible depend largely on the type of 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 as 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 small set of simple discrete 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) had participants construct models with Lego bricks. They focused on their subjects' accounts of what they were thinking, using verbal protocols exclusively and did not code the different physical actions performed such as joining, disjoining, rotating or sorting bricks.

Methodology

Experiment Setup

In our experiment 9 participants were given 15 minutes to build a physical model of their dream house by arranging blocks on a wooden site model (Figure 1). Participants were supplied with 44 3D printed parallelepiped-shaped blocks and free to use as many or as few as they wished. The parallelepiped shape enabled fairly complex assemblies with varied spatial relationships. No other tools or medium (e.g. no pencil or paper) was allowed. Prior to the start of the experiment subjects were given a minute or two to familiarize themselves with the look and feel of the blocks and told that during the experiment it would be helpful if they voiced aloud their thoughts concerning their design or their process as they manipulated blocks. Video/audio was captured looking down on the site model and photographs were taken throughout each session.

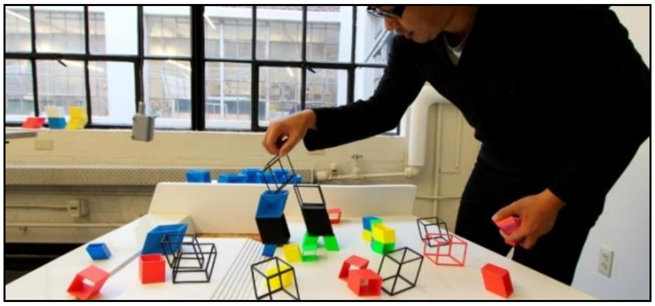

Figure 1: Experiment site model and 3D printed blocks.

Participants

Of the nine participants three were architects with four to eight years of professional practice as well as teaching experience at the graduate level. The six student participants were spilt into two groups. Three students were undergraduates majoring in architectural design, and three were undergraduates from non-design related departments.

Table 1: Study Participants

Experienced architects	3	3M, 0F
Students in architecture	3	1M, 2F
Students in non-design fields	3	2M, 1F
Total	**9**	**6M, 3F**

Hypothesis

Our hypothesis was that in an exploratory design task requiring physical manipulation, there will be significant differences between the way architects and students interact with their materials. The nature of these differences should be discernable through a coding scheme and connect in some way with the strategies different skill levels rely on.

Coding Scheme

Our coding scheme treats interaction with a block to have three parts: a picking up step, a manipulating step and a placement step. Within this broad activity structure or ‘framework’ we distinguish four types of actions and then seven distinct interaction sequences.

Primitive Interaction Types There are four interaction types: *adding* blocks to a configuration, *subtracting* blocks from a configuration, *modifying* blocks within a configuration, and *relocating* blocks across the site. For our purposes we abstract from details of how a block was picked up, manipulated and placed and focus instead on where it came from and where it ends up. Each of these four types is defined by the locations of the picking and placing actions as identified in Table 2. For each participant we counted each occurrence of the action type and measured its duration.

Interaction Sequences An interaction sequence is an ordered set of primitive interactions over time. There are two types of interaction sequences:

- *Linked interactions* occur when the same block is acted on two or more times in a row. For example, when a subject adds a block to a configuration and without really putting it down, does a modify action (turns it) we say the two actions are linked. Or when a block is put down then taken away, even if there is a delay, two actions are linked.
- *Non-linked interactions* occur when subjects pick up different blocks. When the actions are different the sequence is a simple non-linked sequence. When the same action is performed three or more times on different blocks – e.g. Add-Add-Add – we call the sequence repetitive.

See Table 3 for all interaction sequence definitions.

Table 2: Definition of interaction types

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 blocks within configuration only
RELOCATE	Site	Site	Participant moves block across the site

Table 3: Definition of Interaction Sequence Types

Interaction Sequence	Name	Interactions Involved
Non-linked Repetitive	Manage	Relocate-relocate-relocate
	Disassemble	Subtract-subtract-subtract
	Assemble	Add-add-add
	Explore	Modify-modify-modify
Linked	Test:Reject	Add-modify-subtract
	Test:Accept	Add-modify
	Test:Eject	Modify-subtract

Results

Despite our small sample size there were important differences between the three participant groups. At a structural level there were clear differences in the block count, block variation, and block arrangement of the final model. At a protocol level there were suggestive differences but variance in the quantity of talk aloud results prevented us from finding anything more than anecdotal differences. At an interaction level, however, there were clearer differences in the primitive interaction counts as well as trends in the interaction sequences across the three groups.

Dream House Models

Figure 2 shows renderings of the participants’ final models. Each rendering is an orthographic projection of the model.

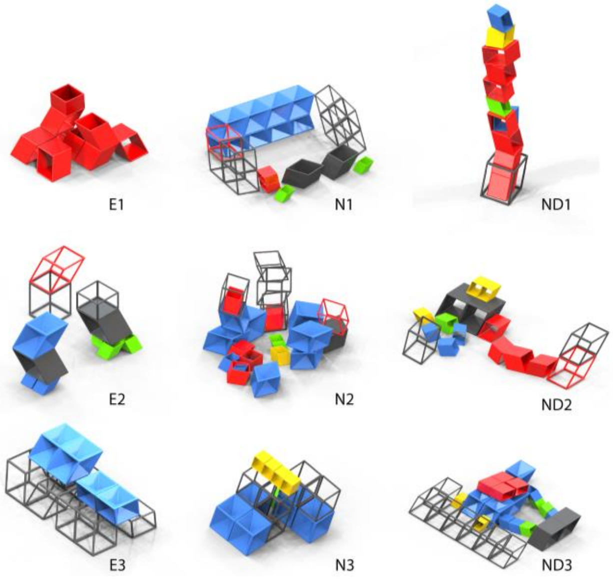

Figure 2: Renderings of models by architects, left; novices, middle; and non-design students, right.

Block Count Architects tended to use fewer blocks in their completed models than the other two groups. Mean number of blocks used: architects = 11.0, novices = 17.3 non-designers = 19.0. Novices and non-designers tended to keep adding blocks to their configuration until the supply ran out. Experts seemed to identify a limited set of preferred blocks, e.g. all red blocks, and then worked with those alone.

Block Variations Similarly, architects used fewer types of blocks. Of the ten distinct types of blocks: architects used 3.3 types (mean) in their final model, novice student designers used 6.3 (mean); and non-design students used 7.3 (mean).

Verbal Protocol Analysis

To explain the differences in behavior we looked at the content of what was said to see if there were differences in design approaches of the different groups. The key difference we found is that architects take a more abstract approach, thinking in broader architectural concepts than students (as one would expect), whereas students think less about the spatial and structural properties of shapes and more concretely about the function of a placement in an emerging structure. Non-architects seem to explore less and in a less abstract way.

For example, one novice design student (see subject N1 in Figure 4) described her process as one of using blocks to represent typical household features – specific functional units:

> "I'm using this [block] as the entrance…and I'm going to use these [blocks] as the grass and flowers…and these [wireframe blocks] will be windows"

A non-design student (ND3 in Figure 4). voiced a similar approach, expressing practical concerns about the 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"

Furthermore, ND3 was thinking about particular 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."

Architects had a different approach. They commented on the how moving shapes around facilitated their exploration of the spatial relationships between blocks. E2 started off his design session by saying:

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

He was giving himself a constraint – joining the blocks face-to-face – and seeing what relationships became apparent.

E1 remarked very early on in the session:

> "I like that these [the red blocks] 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" .

He was thinking sculpturally of the external shape of his model in relation to the site in which it is situated, and simultaneously thinking about how the blocks seem to define an interior space that is confronted differently by someone on the inside. The same architect emphasized that he conceptualized the inside too in a more abstract manner,

> "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."

Architects seem to use the blocks to visually and kinesthetically fish for abstract structural ideas and relations. They don't have a clear idea of what they might be making first and then assemble blocks to see if it works. Rather, they use the blocks to throw up ideas that they can evaluate as interesting or not.

Interaction Results

To determine whether expertise was revealed in other quantitative measures we first coded each participant's video session in terms of primitive interactions (Add, Subtract, Modify, or Relocate), looked for differences in summary statistics, and then analyzed sequences. In Table 4 we show the number of times each action was performed by a subject and the percentage of all actions that action represents. E.g. E2 performed 27 Add actions; these accounted for 24.5% of all of his interactions.

There was huge variance. Total number of actions for the nine subjects range from 44 to 162. These counts vary across and within each group and depend largely on the amount of time spent in the task. Total time spent acting on blocks for each participant ranges from 113 to 429 seconds.

We did a Chi-Square analysis to test the null hypothesis that that there is no significant relationship between participant group and interaction count. The result is $x^2(6, n=9) = 32.22$ $p < .01$. This low probability is sufficient to reject the null hypothesis. But what is the relationship?

Owing to the small sample size and significant individual differences results were suggestive but inconclusive at the summary level. Figure 4 reveals that both architects and novice architectural students perform Modify actions more often than Relocate actions. For instance, they will position a block one 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. This has the effect of displaying more block relationships. Non-design students, on the other hand, interact with blocks more often on an individual basis, isolated from a developing configuration. Non-designers seem to experiment less.

Interaction Sequences

Differences between architects and all other subjects show up more clearly when we look at sequences of action. Overall, architects spend a greater percentage of their block activity performing linked interactions than both novices and non-designers, and suggestively novice designers likewise perform more linked actions than non-designers: architects 60.7%, novices 50.8%, and non-designers 43.8% (Figure 5). That is, action spent thinking and manipulating the same block varies with expertise, the more expert the more actions on the same block. This is consistent with the tendency to experiment. Looking Figure 6, there is a clear trend correlating expertise and the tendency to test and reject a placement, and test and eject a placement.

Table 4: Interaction primitive results per participant by group

Interaction Type	**Architects**			**Novices**			**Non-designers**		
	E1	**E2**	**E3**	**N1**	**N2**	**N3**	**ND1**	**ND2**	**ND3**
# of ADD actions	11	27	16	42	36	26	21	22	33
% of total	25.0	24.5	28.1	28.6	22.2	24.5	39.6	23.9	31.1
Time (s)/action	1.0	1.0	1.0	1	1.1	1	1.2	1.1	2.5
# of SUBTRACT actions	4	12	4	9	13	9	6	5	7
% of total	9.1	10.9	7.0	6.1	8.0	8.5	11.3	5.4	6.6
Time (s)/action	1.0	1.0	1.0	1.0	1.5	1	1	1	1
# of MODIFY actions	19	39	20	59	90	35	13	31	17
% of total	43.2	35.5	35.1	40.1	55.6	33.0	24.5	33.7	16.0
Time (s)/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	36	13	34	49
% of total	22.7	29.1	29.8	25.2	14.2	34.0	24.5	37.0	46.2
Time (s)/action	1.1	3.5	1.4	1.9	2.0	1.4	2.4	4.7	1.8
TOTAL ACTION TIME (s)	**130**	**410**	**113**	**429**	**340**	**243**	**126**	**335**	**227**
TOTAL ACTIONS	**44**	**110**	**57**	**147**	**162**	**106**	**53**	**92**	**106**

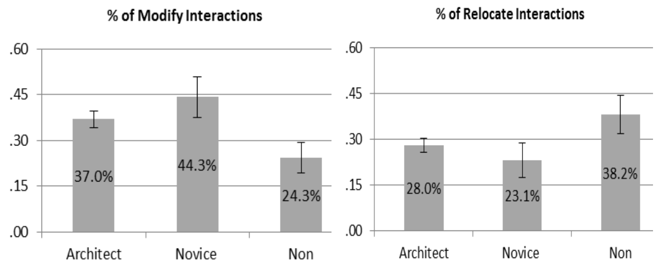

Figure 4: Percentage of Modify and Relocate

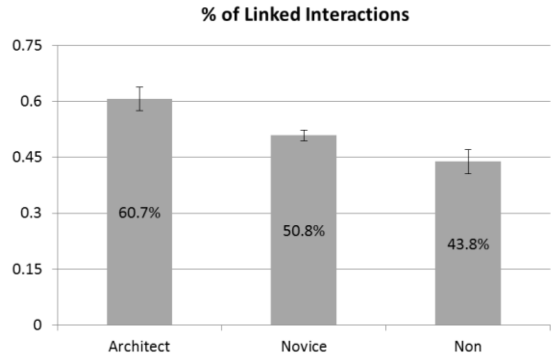

Figure 5: Percentage of Linked Interactions

Architects perform over two times as many Reject interaction sequences and over three times as many Eject sequences compared to non-design students. It seems the architects are more selective when choosing which blocks to keep in the model.

This also correlates with the tendency to devote less activity to managing and assembling blocks. Non-design students perform Assemble interaction sequences seven times as much as the architects. On the whole, architects, more so than the other groups, employ interaction strategies which link longer chains of related interactions.

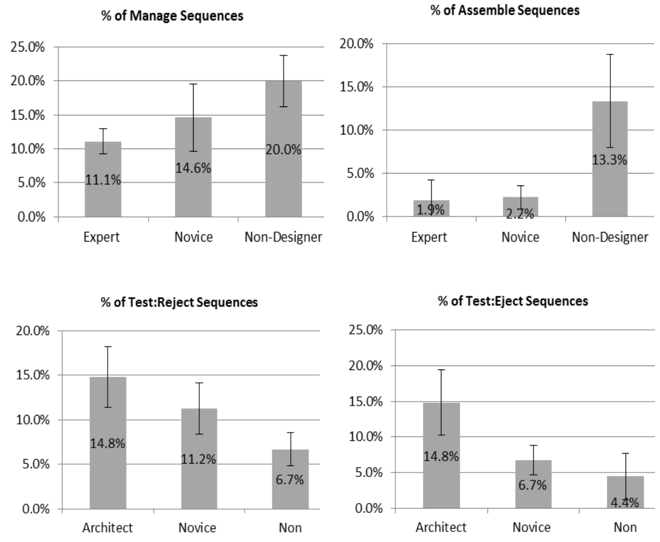

Figure 6: Percentage of Non-linked (Above) and Linked (below) sequence types by group.

Discussion

Robots are becoming increasingly available to architects and designers. So far their role is to help build parts and assemble models. Why not integrate them in the early exploratory stage of design (Figure 7)?

The challenge in bringing robots in as cognitive collaborators and not just as hired hands, is that joint action normally requires collaborators to know what each other is doing. That is still a long way off. But as our study has shown, architectural designers interact with physical material in characteristic ways – certainly in ways that are distinguishable from students. These can be coded in terms of primitives and sequences and as more regularities are discovered a theory of 'thinking through material interaction' may become the framework through which designers may creatively work with robots.

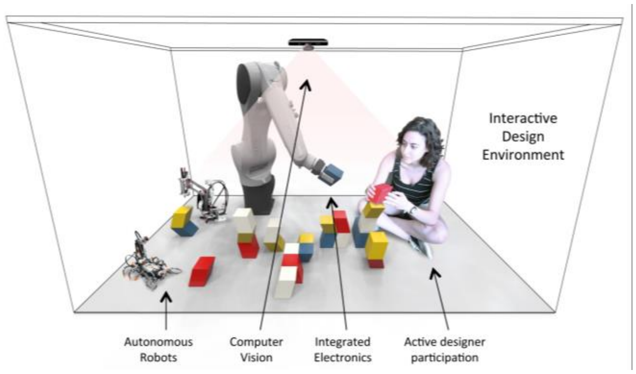

Figure 7: Vision for an interactive robotic arm

Equipped with vision sensors and object recognition functionality, robotic tools could observe a designer's material interactions and track the emerging structure of his or her model. At first the value of this tracking would be to support low cost undoing or duplication. A robot could quickly duplicate interactions or perform iterations and variations of the designer's moves, enabling rapid prototyping of variations or construction of symmetric configurations. But additionally, a robot can be used to compute complex arrangements that are hard to imagine and difficult to manually configure, such as assembling block arrays or reflections. This will be especially beneficial as materials themselves become more designed and complex. A robotic partnership could expand the visualization and manipulation capacities of architects and give room for new thoughts.

Conclusion

In order to understand how architects work with physical objects to visually and kinesthetically explore design possibilities, we 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 contours and a set of forty-four different shaped, sized and colored blocks. We devised a coding scheme to analyze the material interactions of designers and this world based on three basic actions: picking, manipulating, and placing blocks on the site. Using this scheme we were able to distinguish the interactions exhibited by architects from novice students and non-design students.

Our 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 collections of blocks. They also consider other architectural concepts such as negative space. 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 parts of houses. This difference in concern leads architects to experiment with space differently.

Our second observation is that the amount of activity spent experimenting and fishing for new ideas, seems to correlate with design experience. Architects more than novices and more than non-design students use 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.

A blocks world is inevitably a limited design world. We believe our results are suggestive enough, however, to show that subjects use blocks to think with. If our goal is to develop robotic cognitive assistants frameworks such as ours will need to be further developed and elaborated.

Acknowledgments

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