ABSTRACT
Despite the advancement of digital design and fabrication technologies, design practices still follow Alberti’s hylomorphic model of separating the design phase from the construction phase. This separation hinders creativity and flexibility in reacting to surprises that may arise during the construction phase. These surprises often come as a result of a mismatch between the sophistication allowed by the digital technologies and the designer’s experience using them. These technologies and expertise depend on one human sense, vision, ignoring other senses that could be shaped and used in design and learning. Moreover, pedagogical approaches in the design studio have not yet fully integrated digital technologies as design companions; rather, they have been used primarily as tools for representation and materialization. This research introduces a multisensory computational model for human-machine making and learning. The model is based on a recursive process of embodied, situated, multisensory interaction between the learner, the machines and the thing-in-the-making. This approach depends heavily on computational making, abstracting, and describing the making process. To demonstrate its effectiveness, I present a case study from a course I taught at MIT in which students built full-scale, lightweight structures with embedded electronics. This model creates a loop between design and construction that develops students’ sensory experience and spatial reasoning skills while at the same time enabling them to use digital technologies as design companions. The paper shows that making can be used to teach design while enabling the students to make judgments on their own and to improvise.
INTRODUCTION

Over the past decades, digital design and fabrication technologies have emerged from being merely tools for representation and materialization to shaping design practice itself (Llach 2015). However, even with the advancement of these technologies, architecture practice still follows Alberti’s hylomorphic model of separating the design phase from the construction phase. In this linear process, the design phase stops when representations and execution drawings start. However, despite meticulous advanced planning using digital tools, surprises may still arise on site during construction. One of the reasons for these surprises is that the effectiveness of digital technologies depends on the designer’s experience and on one human sense: vision. It is expected that the designer will be aware of the physical aspects of their design: materiality and structure, and phenomenological aspects such as experience, delight, and gravity. Even simulation software depends on representation and the designer’s sight.

The same hylomorphic model is applied in the design studio. Students are trained to represent their designs using 2D drawings and physical and digital models without understanding how their designs will be constructed or whether they are buildable. While several educational institutions offer courses in learning the technical skills for using digital fabrication machines, students are encouraged to build prototypes without fully understanding how they might actually be constructed. This separation between design and construction in the architecture studio hinders creativity and limits the students’ capabilities for learning to predict whether or not their designs are feasible. The pedagogical methods in the design studio have not yet adapted to integrating these technologies so that they engage all the student’s modalities in learning. In order to learn about materiality, structure, tectonics, and spatial aspects, students need to interact physically with the things being designed, not merely view their digital representation on a screen.

In order to enable students to build their sensory experience and spatial reasoning for a holistic approach to design, a new pedagogical method is needed that is based on embodied, sensorial interaction between the learner, the machines, and the thing-in-the-making. In this paper, I introduce a multisensory computational model for learning and making that creates a loop between design and construction, and shapes the student’s design knowledge and spatial skills using any tool or medium, whether digital or manual. The model integrates rule-based thinking and is based on the notion that learning to design and make depends heavily on action and perception. I define making here as the situated, embodied action that unites both design and construction. To demonstrate the effectiveness of this computational model, I present case studies from a course I taught at the Massachusetts Institute of Technology (MIT) this year. During the course, entitled Making Spaces: Lightweight Structures for Interactions, students built full-scale lightweight structures (Figure 1) with embedded electronics for interactions (Figure 2).
COMPUTATIONAL MAKING AND THE COOKIE CUTTERS

Most digital fabrication machines in educational institutions and architecture schools are used as cookie cutters, materializing already designed drawings. Other courses focus on teaching the technical skills necessary to use the machines without focusing on the design aspect of the learning process (El-Zanfaly 2015). However, some researchers and educators have highlighted the importance of focusing on analytical thinking in digital modeling and fabrication as a design process in itself (Özkar 2007). Others have treated physical prototypes produced by digital fabrication machines as generative tools for design explorations (Diniz 2015). Other experiments have included adding a “human touch” to human-machine interaction in digital fabrication by building full-scale structures on site using a hybrid system that combines human movements, materials, tools, and a feedback loop (Lopez et al. 2016).

In this paper, I focus on an embodied approach for making, and learning to design through making. This approach depends heavily on computational making, abstracting and describing the making process, including both the machine and human actions of making. We often fail to keep track of what we are doing and how we are making a thing during the action and process of making itself. We become so involved in what we are doing that we are often not mindful of our actions or why we are taking them. A rule-based design approach helps us describe and reflect on the making process at every stage of the computational model, which in turn helps us generate new designs.

Terry Knight and George Stiny (2015) introduced making grammars as rules or algebras for making things based on shape grammars (Stiny 2008). To explain computational design and rule-based thinking, I introduce shape grammars and visual rules for students to use in describing their making processes. I always demonstrate how explaining a cooking recipe is more effective than handing someone a list of instructions. I use laser-cut cardboard pieces for hands-on exercises to demonstrate how to create physical rules, generate a small thing with those rules, and describe the whole physical making process visually (Figure 3). I chose cardboard pieces because they allow the learners to go beyond symbolic one-dimensional pieces; students can cut or fold the pieces if they want.

I³: A MULTISENSORY COMPUTATIONAL MODEL

This computational model was developed through ongoing research at MIT (El-Zanfaly 2013; El-Zanfaly and Knight 2016; El-Zanfaly 2015). It is called I³ for its three-layered operation of Imitation, Iteration and Improvisation. I³ starts first with the Imitation stage, asking students to choose and analyze a precedent, then try to make it with any materials or tools at hand. The Imitation could be to make an exact copy of a thing, copy a design concept, or copy from more than two things. Second, in the Iteration stage, learners are asked to make several guided iterations of the things. In each iteration, learners must change only one aspect of the thing, such as its material or geometry. In the third stage, learners improvise and produce another final iteration or a completely new thing (Figure 4). In general, once learners finish the iterations, they have enough experience to be able to improvise and make decisions about future steps.

Development and Testing

As a start, I closely studied the interaction of novice designers and students with digital fabrication machines and their making process. Afterwards, I conducted experiments through teaching in several educational institutions to further develop
and test the computational making model. In the first course, Computational Making: Light and Motion, taught in consultation with MIT Professor Terry Knight in Spring 2015, we began by having students make a small thing: an interactive lighting unit. The students designed the lighting units to react to external changes occurring around them by changing their physical shape or lighting state. We used I³ as the course structure, and we led the students through a process of first imitating an existing lighting unit, then making four guided iterations of it, gradually improvising on their existing unit or creating an entirely new one (Figure 5). During the course, the students used visual rules to describe and document their making processes. As this was the first course to implement and test I³, I wanted to observe where it was effective and what I might need to change in future courses. In the second course, the thing-in-the-making became larger: a scaled playing space for children. The course was offered as an architecture studio for second-year architecture students at Istanbul Technical University in Turkey in Fall 2015. I wanted to see how I³ could be implemented in an architecture studio to teach not only design but also digital modeling and fabrication skills. In the third course, Making Spaces: Lightweight Structures for Interactions, given in January 2017 at MIT, the thing-in-the-making became a lightweight structure occupying a space of approximately thirty cubic feet at full scale. In this course, I wanted to examine and develop the computational model in the context of building larger structures. Specifically, I wanted to add scale as a major element and observe how students would react to scaling up their prototypes.

Imitation
I define Imitation here as the act of mindfully copying a thing, either fully or partially. Learners can choose or be instructed either to copy the entire thing or only a part of it. If they choose to copy the entire thing, they must use the same materials, geometry, structural elements, assembly, design concept, and fabrication technique, if available. In I³, Imitation is a first stage for jumping in and breaking the ice with the design and fabrication media. Instead of spending time deciding what to make and what details to include, learners have something to begin making. Once they start, they learn the basic technical skills of using the digital and manual tools to realize what they are trying to make. Imitation includes observation, analysis, and interaction, all of which involve the senses and movement.

As they make, learners observe and analyze the details of how things come together, and how to assemble the structure and attach the parts. They decide on the exact location of each part, estimate approximate dimensions, test physical and material behaviors, and see how to first draw and then fabricate a specific geometry. While interacting with the tools, machines, and materials needed to make the thing, students use their bodies to sense and learn.

Iteration
I define Iteration as the making of another copy of the thing already made in the Imitation stage, but adding something new to it or changing it in some way. Iteration here is guided: in every iteration made, everything must be kept the same, except for one feature and whatever depends on that feature. This changed feature could be in material or geometry, or in the scale of one element—and whatever depends on it. In I³, students must make at least three iterations in order to have the opportunity to experiment with several design and making aspects, and to interact with several tools.
For example, changing one feature may lead to changing the material, which in turn can lead to learning about a material behavior different from that of the original material used. This change might also lead to a change in the structure or geometry that was shaped by the original material. These changes might also lead to learning new fabrication techniques and technical skills. Making an iteration that enlarges the scale, for example, would lead to moving from laser-cutting a sheet of acrylic to milling wood on a CNC router.

To give an example from the course, a group of students calling their project "The Briar" moved from paper, which they used in the Imitation stage, to laser-cut clear polystyrene in the first iteration, to a one-eighth-inch flexible wood sheet cut on the CNC router in their full-scale iteration (Figure 6).

Improvisation

Improvisation is open ended. Even in the Imitation and Iteration stages, improvisation exists, although its level increases with every stage. The learners’ making and sensing abilities increase during I until they can create something of their own. In the Imitation stage, fewer surprises occur; learners are copying a thing that they already see. Surprises come from the fabrication process, when students use the machines or tools or deal with unexpected structural or material behavior. Learners must react to solve the emerging surprises to build their copy of the thing. In the Iteration stage, learners face a new challenge in choosing what to change in each guided iteration, and how to modify it in reaction to the surprises arising from that change. Thus, improvisation increases with every iteration made. Improvisation reaches its maximum at the final stage, where learners are not provided with any guidance. By the time the students have reached this stage, they have learned the skills that they can apply to new projects in new contexts.

In Making Spaces: Lightweight Structures for Interactions, the Briar Group faced a new challenge. Although they had tested some parts of their structure at full scale (Figure 7), when they started building the final structure they realized that the wall pieces would not stay in their allocated slots in the base because the material weight was putting unexpected tensions on the entire structure (Figure 8). Thus, they had to improvise and add wooden pieces to the base in order to hold the wall in place (Figure 9).

MAKING SPACES FOR INTERACTION

I applied I in teaching the Making Spaces course, in which students built full-scale lightweight structures that included embedded electronics. The students’ backgrounds varied: there were two first-year Master of Architecture students, undergraduate architecture students, undergraduate students with an undeclared major, and one undergraduate student in mechanical engineering.

This was the first course in which all students were instructed to build large structures scaled 1:1. Some students had background in programming and some had some digital modeling and fabrication experience, including using a laser cutter for architecture studio models. During the course, we used the fully equipped digital fabrication lab in a design center at MIT. Because of the
time limitation of the course, I ordered most of the material in advance, leaving other materials to be ordered depending on the projects’ needs.

The course lasted only two weeks; there were nine daily six-hour sessions. On the first day, I introduced the course objectives and goals, explained I, and showed examples of lightweight structures and pavilions. I handed students a questionnaire about their skills and explained my expectations for the class. I introduced shape grammars and visual rules, and gave a hands-on exercise with the press-fit kit to demonstrate how to apply and describe rules. Finally, I handed them their first assignment; first, to build a scale enclosure using the press-fit kit pieces and define the rules used; second, to choose five examples of lightweight structures from which they would choose one to imitate and build with dimensions around 10 x 10 x 10 feet, and with a prototype scaled 1:8.

At the end of the second day, students presented their projects; we then voted on the top three projects and students formed three groups to work on these projects for the rest of the course. In the second assignment, I asked the students to choose one element to change in their project. I explained that the change could be, for example, a change in geometry or in the dimensions of a structural element. The only constraint was that they could not change the material. The students presented their first iteration at the end of the third day.

In the third assignment, the students had to make a second iteration of their project. This time, they were to keep everything the same except the material of one element and whatever depended on it. I explained that they could change the material of the structure of the skin from paper to wood or corrugated cardboard, for example. I added that this material should be the final material to build the space with, so any scale would work as long as it was larger than 1:8. The second part of the assignment was to draw a storyboard to show how users would interact with their space. In the third iteration, I asked the three groups to build parts of their spaces at 1:1 scale with the final material. Finally, I advised each group separately as they progressed with their projects. On the last day, I handed them the review guidelines, and we had a final review with an invited panel.

In all the stages, I indicated in the assignments that they had to use visual rules, sketches, or any medium they chose to describe their design and making process, showing what they had kept and what they had changed.

THE BRIAR GROUP
The students in the groups had different skills and backgrounds.
The first group called their structure “The Briar,” and the group consisted of one undergraduate student from mechanical engineering, another from architecture, and a freshman with an undeclared major.

The students worked individually for the first two sessions, and then formed groups. The group worked on an Imitation stage produced by one student before forming the group. The Imitation stage was inspired by “Whiplash” by Patrick Dougherty and “Dragon Skin Pavilion” by Tampere University (Figure 10). As a group, the students worked on making the first iteration. As instructed, they had the freedom to change the geometry of their structure while keeping the material and everything the same. The group changed the geometry of the modular unit of the structure to create an enclosure inspired by nature (Figure 11). Although students were asked make only one guided iteration per session, the group made several. They laser cut the modules in paper, which facilitated the iteration process. They then moved from using paper to using 1/8-inch-thick flexible polystyrene. Since they were planning to use plywood sheets as the final material, polystyrene was chosen as a transitional material with which to test their geometry (Figure 12).

Once they used polystyrene, they realized that their geometry needed adjustment to react to the newly added forces of the structure and gravity. They also realized that they had to add a base to hold the structure. In the fourth iteration, they had to use the final material and build part of their structure in full scale. In this step, they had to learn how to use a CNC router and test two types of plywood to see which one would work best with their structure. This helped them to make decisions and to adjust their geometry further. As shown, in every step their ability to react to the changes grew. Assembling the parts together in the final stage (Figure 13), they realized that the tension and compression forces with the wood were causing the structure to come out of the base. They had to improvise and add small pieces to hold the structure to the base. While working on the physical structure, the group started developing a scenario for how the users would interact with the space, and how the space would respond in return. They created a system in which after the user knocks on the surface of the structure, LED strips from the base light up and the walls play sounds like those of a jungle. Although the system worked, they needed more time to integrate it better into the structure.

**THE FEELER AND THE TRIANGLES GROUP**

The second group consisted of three students who named their structure “The Feeler” (Figure 14). The group consisted of two first-year Master of Architecture students and an undergraduate architecture student. They decided to create a game in which the structure would move and play with the users. In their process, they experimented and developed a moving structure, thus focusing on developing an intangible aspect, such as motion, as well as developing the physical structure. The third group, Triangles (Figure 15), consisted of two undergraduate students from architecture and mechanical engineering. The Triangles group developed pyramid-shaped modular units made out of wood and corrugated plastic cardboard. All the units contained multicolor LED strips and some had capacitive sensors: when touched, the units alternated in color from blue to magenta and back to blue again. The students in this group not only developed...
their skills in material properties, but also interacted with the CNC router to mill wood, changing the mill in the router to a blade to cut the corrugated plastic cardboard sheets.

Analysis and Reflections
This research has shown how the computational model 1plaintes design and construction in a holistic, embodied learning process. The work of the students showed that they were always moving from one medium—whether software, machine, or material—to another, in an embodied feedback loop. This feedback loop allowed the students to gain experience and knowledge of material behavior, along with the capabilities of machines and tools. The computational model also proved that it can produce novel and advanced results in a short time. The guided iterations allowed the students to focus on one aspect at a time, and understand how the geometry affects the material behavior and vice versa. The model also proved that it can produce results with students from different majors and different skill levels, from a freshman with no declared major to a Master of Architecture student.

In the second questionnaire at the end of the class, students rated their design skills and their ability to use digital tools in the making process. Some of them explained that they gained the ability to improvise, respond to surprises, and act on the fly. All of them rated progress in their technical skills using digital fabrication machines and tools.
CONCLUSION

In this paper, I applied a multisensory computational model, I\textsuperscript{3}, as a pedagogical approach for design and making. Inspired by the shape grammar approach of seeing and doing, or recursion and embedding, this model presents a new pedagogical approach that can enhance the design studio and design process. Based on the belief that learning is best achieved through direct, embodied interaction of action and perception, the model shows how learners’ sensory experience and spatial reasoning can be shaped step by step through a feedback loop. Based on reflection-in-action (Schön 1983), rule-based thinking can be used to describe and generate designs along with describing the physical process of making. Beginning with mindful copying that moves to introducing guided iterations, learners develop knowledge of material properties and behaviors and gain experience with phenomenological aspects such as light, delight, and motion. They also learn the limitations and capabilities of the machines as their design companions. In every stage of the process, there are more details to be seen and felt, more details to think about, more decisions to be made about the next steps. By the time the students’ improvisation increased in I\textsuperscript{3}, they have gained the skills to react to surprises and make judgments on their work so that they can apply those skills to new projects in new contexts.

We should no longer follow the Albertian notion of “design, then build” in design pedagogy. The multisensory computational model presented here shows that the embodied interaction between the learner, tools, and thing-in-the making offers a holistic, effective approach to developing new design pedagogy.

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REFERENCES


IMAGE CREDITS

Figure 3: Jacquelyn Liu, 2015
Figure 5: Ann Schneider, 2015
Figure 10,11: Katherine Paseman, 2017
All other drawings and images by the authors.

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