CubeExplorer: An Evaluation of Interaction Techniques in Architectural Education

Hyunyoung Song[1], François Guimbretière[1], Michael A.Ambrose[2], Carl Lostritto[2]

[1]Human-Computer Interaction Lab, Department of Computer Science,
[2]Architecture Program, School of Architecture, Planning and Preservation
University of Maryland, College Park, MD 20742, U.S.A
{hsong, francois}@cs.umd.edu   {ambrosem, carllos}@umd.edu

Abstract. During the early stages of architectural training, tangibility plays an important role in developing spatial awareness. In such contexts, tangible user interfaces are believed to provide a significant advantage as they combine the affordances of both the physical and the digital world. We introduce CubeExplorer, a hybrid 3D conceptual aid that combines physical interaction and digital modeling in an effort to complement conventional architectural space-training tools (such as physical materials and digital CAD programs). Using a digital pen as an input mechanism, CubeExplorer lets users perform subtractive 3D geometric operations on a simple paper based cube model while observing the resulting model on a display. The tangibility of the model simplifies navigation and command execution, while the digital interface makes it easy for users to explore multiple alternative designs. To evaluate the potential of such an approach, we conducted a user study in a normal classroom environment where students were provided with physical (wooden block), hybrid (CubeExplorer), and virtual (FormZ) interfaces to complete the same assignment. Our evaluation showed that CubeExplorer combined the advantages of both digital and tangible media. The advantages of CubeExplorer over digital media were substantiated in a follow-up study comparing CubeExplorer and SketchUp in a similar building task.

Keywords: Education, 3D modeling, pen-based interface, tangible user interface

1. Introduction

One of the challenges in introductory architectural education is to develop the conceptual understanding of form and space in abstract ways [18]. Points, lines, and planes are used in increasingly sophisticated ways to describe geometric volumes of solids and voids. To do so, modern curricula are mixing physical media such as wood blocks, and digital media such as CAD programs, to help students discover these basic concepts in introductory classes. Unfortunately, both approaches come with advantages and disadvantages. Wood blocks offer a simplified format palette that they are easy to use, which helps students to focus on concepts. Yet, their physical restrictions might limit the scope of the students' composition. For example, gravity
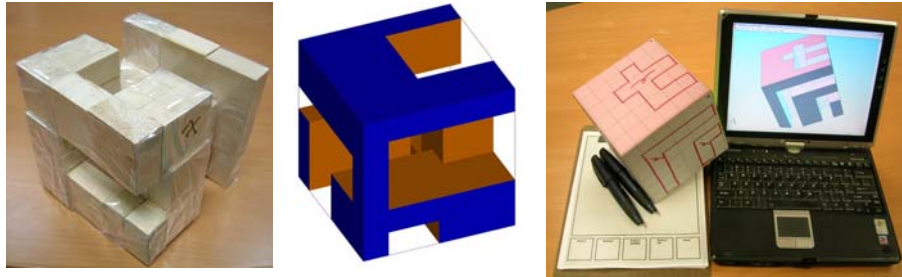
Figure 1 Teaching students how to develop negative figural voids
"The Cube Project", a class project in the Department of Architecture at our university, employed wooden blocks as physical tools (First), FormZ as a virtual tool (Second), and CubeExplorer as a hybrid tool (Last).

forces students to use a bottom up design, requiring students to focus on constructability. CAD tools such as AutoCAD [1], SketchUp [3], or FormZ [2], although not limited by physical constraints, are often complicated to learn and, as a result, limit exploration by novice users. In both cases, users have to adjust their intent to the capabilities and requirements of the tool, which prevents the student from quickly acquiring spatial concepts.

To address this problem, several tangible interfaces [4, 15-17] have been proposed to mitigate the limitations imposed by both physical and virtual tools. For example, digital cube systems [4, 17] allow users to build digital models using tangible cubes. This interaction via direct manipulation [13] makes the basic operations more transparent and reduces the learning curve. However, special equipment is required and only defined sets of operations are allowed.

In this paper, we explore an alternative tangible interface that has a lightweight infrastructure and is well-adapted to the exploration of the concepts of form and space. Using our system, CubeExplorer, students can explore the concepts of void and space by drawing subtractive operations directly on the surface of a paper cube with a digital pen. Commands are transmitted in real-time to a nearby computer which executes them and displays the resulting digital model. A simple, paper-based interface allows students to explore the resulting model, change the visualization style and delete unwanted operations. CubeExplorer offers a transparent means of communication between the designer and the 3D CAD program because the pen input is in the same order that designers conceptualize basic geometry; points, lines, shapes, and objects .

To evaluate the potential of this approach, we conducted a comparative study in an introductory course in the Department of Architecture at our university. We asked students to explore the concept of overlapping voids using three different tools: a set of wooden blocks, CubeExplorer and FormZ, a CAD package used extensively in the architecture curriculum at our university (see Figure 1). Students rated our system as just as easy to use as the wooden blocks, while offering the flexibility of digital modeling when it comes to exploring complex shapes. To explore the role of our choice of FormZ as a possible confounding factor, we conducted a follow-up study to evaluate CubeExplorer in relation to SketchUp [3], a schematic digital modeler designed for rapid design exploration. In this study, participants with limited experience in CAD systems were asked to reproduce 3D models using both

techniques. CubeExplorer proved to be significantly faster than SketchUp for this simple task, validating our results of our first experiment.

2. Related Work

Cube-based tangible user interfaces bring unique affordances to 3D modeling. In these approaches, basic building blocks such as cubes [4, 7, 17, 21] or triangles [19] are augmented with a set of sensors and a communication network which allows the system to automatically infer the spatial relationship between the different blocks. With ActiveCube [17], a user can assemble multimodal cube components, and the system will automatically construct the physical model on a display. This approach makes it possible to automatically transform the appearance of the model to reflect the task at hand [4]. This approach has proven quite successful. Sharlin et al. [12] used the ActiveCube system to assess the 3D spatial and constructional ability of people and showed that the tangible cube system increased participants' spatial awareness. In comparison, CubeExplorer explores the potential of tangible interfaces when performing subtractive modeling, letting users draw directly on the surface of the model to create voids. We believe that both approaches are complementary as both the additive and subtractive processes are important in developing and understanding space.

An alternative approach to simplifying access to digital modeling is to alter sketching practice. Although hand drawn sketches can express every possible blueprint of a conceptual model and are efficient to produce, translating different type of stroke and mapping it to corresponding CAD operation is a tedious process. Several intelligent sketch systems such as TEDDY, 3D Journal and SKETCH [9, 10, 20] have been proposed to bridge the gap between hand sketching and computer-based modeling. Whereas these intelligent sketch systems interpret a two-dimensional drawing as the projection of an intended shape, CubeExplorer, like ModelCraft [14] captures and interprets strokes directly from the model's surface using a digital pen and Anoto pattern paper [5]. This approach offers a more direct mapping between the students' objectives and the actions to be performed on the model, by reducing the navigation burden. Although CubeExplorer was inspired by ModelCraft, the two systems are different. In particular, CubeExplorer explores how the ModelCraft command system can be extended to real-time settings in which commands are reflected on a nearby computer. Also, to adapt to the constraints of a teaching environment, CubeExplorer does not offer the full set of ModelCraft commands.

Because interaction with physical artifacts is essential for architects, several tangible workbenches for manipulating digital representations have been proposed. Luminous Planning Table [16] simulates the shadows and reflections on top of physical architectural models while users modify the position of the model on a table surface. Illuminating Clay [11] allows user to alter the topography of a clay landscape model using traditional techniques. The system automatically captures the resulting surface and projects the results of the analysis back onto the clay landscape. The focus of these interfaces is more on collaborative work where interactions are mediated through physical proxies. CubeExplorer, in contrast, is focused on the representation

of basic geometry and 3D operations in architectural education. However, the two approaches could be easily integrated.

3. "The Cube Project" in a Classroom

Teaching students how to think in three dimensions is an essential part of introductory architecture curricula. One component of this type of spatial thinking is the ability to understand different types of space: solid (interior of a frame), void (subtraction of a frame), and overlapping (intersection of two frames). "The Cube Project" is a classroom activity for introductory architecture students that aims to give insight into the understanding of space. The activity was designed to train students to configure different types of *figural voids* (Figure 2) in a single cube and understand the composition of the interior, specifically overlapping spaces.

The project fulfills several goals: First, it lets students explore the implications of 2D manipulations (such as orthographic projection) on a 3D design, and observe how different manipulations might interact. Second, it introduces students to the role of abstraction and representation in different media by using 3D planning tools to create different figural solids/voids. For example, void space, which is an abstraction of a physical or virtual cut, can be configured by removing individual cubes from a block of cubes (physical media), or using constructive solid geometry (CSG) operations in a CAD program (digital media). Third, it helps students develop conceptual clarity by performing these operations in different environments.

To fulfill the requirements of the project, several approaches have been used in the past. One approach was to use physical wooden blocks. This solution is appealing for its simplicity, but unfortunately, physical tools have a ground plane constrained by

Figure 2 Figural Solid, Void, and Overlap

gravity which limits the range of figures that can be constructed and explored. Furthermore, wooden blocks do not encourage students to explore the relationship between 2D and 3D manipulation. Another approach is to use CAD programs, which are more flexible and will be used extensively later in the curriculum. Yet current CAD programs are often difficult to learn because their conceptual model requires understanding advanced concepts.. Without a thorough understanding of these concepts, CAD programs are often difficult to use. This fundamentally limits their use in introductory curricula because the complexity of their interfaces (in particular the navigation interface) can be distracting to students.

The design objective of CubeExplorer was to create an interface combining the positive features of both tangible and digital approaches. To do so, CubeExplorer captures input on tangible models (in this case, paper cubes) and displays the electronic results on a display where user can take full advantage of the digital
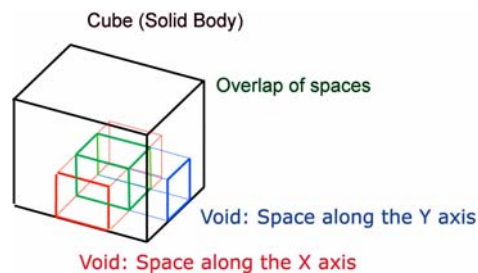
representation (such as the ease of undoing one's work). A unique feature of CubeExplorer is that it encourages users to understand the spatial implications of a sketch drawn on the surface of a cube. This fosters the conceptual understanding of overlap among voids expressed in the reference frames of each of the six faces, with different implications in each frame.

3.1.   CubeExplorer Interface

The CubeExplorer interface consists of three main elements:

- A paper cube whose faces are covered with Anoto pattern [5] paper that can be recognized by a Logitech io2 pen. The pen transmits the strokes drawn on the surface of the cube directly to a computer through a Bluetooth link.
- A paper tool palette, also covered with Anoto paper. The palette is used to control the orientation of the cube on the screen, and to perform operations such as changing the display style or undoing operations.
- A computer which receives input from the pen display and executes the results. The computer runs SolidWorks as the underlying CAD software. The specific CAD package is not important here as users do not need to interact directly with SolidWorks while using the system.

Using this configuration, users can complete the Cube Project using only the Logitech io2 digital pen and the paper cubes as input devices.

Shape	Depth	Pigtail
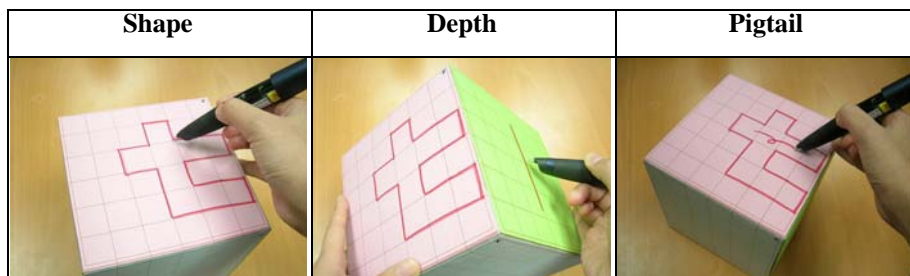
Figure 3 Operation Syntax for the Cube Explorer system
The Syntax for the cut feature consists of shape, depth, and pigtail. The result of the operation is shown in Figure 1

To create a void, users simply draw the shape of the volume to cut on a side of the cube. This sketch becomes the basis for the subtractive operation. Then, users draw the depth of the cut on any perpendicular surface, and mark the area to cut using a simple pigtail gesture (Figure 3). If no specific depth is provided, the system cuts though the entire solid. This syntax was inspired by the ModelCraft system [14] from which our system is derived. As in ModelCraft, the last pigtail lets users indicate whether the inner or outer part of the shape should be used for the cut operation.

When the user starts marking, the model on the display automatically rotates so that the face being drawn upon is shown. As users draw the shape to be cut, the system provides immediate feedback via ink on the surface of the 3D model on the screen. The ink is accumulated until the system detects a closed shape. At this point,

the system beeps and replaces the ink on the screen with the final shape to be cut. Operations are executed as soon as a pigtail is detected. Different tones of beeps are used for each command element (shape, depth, and pigtail). This makes it possible to use the interface without looking at the screen.

The paper-based tool palette is composed of two main areas. On top is a navigation pad. Pen input in this area is used to rotate the model on the screen. At the bottom of the palette we implemented a series of paper buttons (similar to Anoto's pidgets[5]) to help users during their work. The "View mode" button let users toggle between shaded and wire frame views. Users can select cuts in one of two ways: either by drawing a pigtail inside of the drawing which generated the cut, or by using the "Up" and "Down" buttons to move through the list of cuts presented on the left of the screen. The "Delete" button lets users delete the currently selected cut. The interface also provides a "Reset" button to reset the internal state of the command system if needed.

3.2. Implementation

The system was implemented as a plug-in for the SolidWorks CAD program. One of the major challenges we encountered was to ensure that the free form input provided by users could be interpreted correctly by the system. Human sketches are ambiguous in nature, whereas CAD requires precise parameters [8]. The Cube Project's requirement that all cuts be performed on a grid simplified the amount of processing of input required before calling the SolidWorks API functions. We simply determined which edges in the grid matrix were closest to the pen strokes and used them as the function parameters. When the user finishes drawing a closed shape on the surface of the model, the free-form ink on the screen is replaced with a shape snapped to the grid. For a system with a more relaxed set of drawing constraints, a more complicated approach such as Arvo's Fluid sketches [6] would be required.

Since CubeExplorer uses a simple paper model without a tracking system, users are required to align physical and digital models separately. Because a cube is a symmetrical object with respect to each face and the four orientations of each face, users may easily become disoriented. To differentiate among the faces, different colors are assigned to corresponding faces in the paper and the screen model. The orientation within each face is indicated by a cross symbol at the lower right. When a user starts drawing on the desired color face, the cube on the screen automatically orients to the corresponding face and direction. When the user writes on a different surface, such as creating a depth mark, the cube rotates automatically to render both faces on the screen.

4. Evaluation

To evaluate the potential of CubeExplorer to complement conventional architectural education tools, we conducted two experiments. In our first experiment, we compared CubeExplorer to the use of wooden cubes and FormZ, a CAD program, used

extensively later in the curriculum. As our findings may depend heavily on the choice of the CAD program used, we complemented our evaluation with a second experiment, comparing the CubeExplorer system to SketchUp, a CAD program specifically designed for quick spatial exploration.

4.1. Experiment I

The goal of this experiment was to evaluate how students benefit from three different 3D tools (wooden blocks, CubeExplorer, and FormZ) when performing the Cube Project. Our hypothesis was that CubeExplorer would offer a synthesis of the advantages of the tangible solution (ease of navigation, ease of parameter specification, limited indirection) and the fully digital solution (relaxed physical constraints, ability to undo or save a snapshot of one's work). As a second hypothesis, we predicted that the unique reference system of CubeExplorer would encourage further exploration by facilitating the spatial cognition process in 3D.

4.1.1. Task and apparatus

Students were instructed to start with a 6" solid cube and to remove parts of it either in physically setting, virtual setting, or hybrid setting until finalizing their design. The design goals were as follows:

1) Modify the cube using a subtractive process.
2) Create three figural voids that overlap each other within the cubic volume.
3) Demonstrate a strategy of spatial organization that conceptually connects the figural voids of the cube.

To compare the three experimental settings, each task involved a 6" cube which was either decomposed in 1'' increments (physical model) or had a grid system with snap intervals of 1" (hybrid and virtual models). Thus, every operation performed on the solid body had the resolution of 1"; the atomic unit of any construction was a 1" cube. We considered 3 conditions:

- *Physical Model Method:* Wooden blocks were used to demonstrate properties of physical media. We considered several possible options for this condition including foam cubes connected by Velcro or dowels, Lego bricks, Duplo, K'nex and wooden blocks taped together. Foam cubes were too light and are difficult to connect. Many plastic bricks such as Lego enforce a privileged construction direction and are sometimes difficult to disassemble. We finally settled on wooden cubes as they are the most practical. Tangible digital cube systems [15, 17, 21] would have been interesting interface to deploy for this task, but they suffer similar from problems as the plastic brick approach.

  A full 6" cube composed of 216 (6x6x6) 1" cubes was provided for students to remove parts of the cube to create voids inside. The students were instructed to attach different parts such as overhanging cubes with tape. They could also use pre-assembled blocks of 2"x1"x1", 2"x2"x1", and 2"x2"x2". Students could orient themselves around the model to navigate or visualize a cut.

- *Virtual Model Method:* There is a wide variety of CAD modelers that would have been appropriate in this setting. In the end, FormZ [2] was chosen because it allows users to perform subtractive operations without requiring significant understanding of multiple parameters or operations. We also considered using SketchUp [3], a system with a much simpler interface, but found that SketchUp is a surface modeler as opposed to a solid modeler, and was not well-adapted to this task. We explored the possible influence of this choice in our second experiment.

  Each student was given a FormZ template file with a rendering of a 6'' cube. Settings such as the view and the selection mode were optimized for a subtractive modeling process. Creating a cut involved three basic steps. First, students created 6-sided orthogonal 3D extrusions from the ground reference plane defined by the system to make the "cutting" object. Second, they used the "move" tool to position the cutting object in the desired position. Finally, students issued subtractive geometry operations to cut the "cutting" object from the "original" object.

- *Hybrid Model Method:* Each student received a 6" cubic box covered in Anoto paper, along with a digital pen and the navigation palette described above. Spare boxes, pens, navigation palettes were provided upon request. Using these tools, students created figural voids inside the cube on the screen by drawing on the surfaces of the physical model. Students had to hold the pen against the surface of the paper model at a right angle that maximized the pen's capture area. The digital paper palette was used to interact with the digital model shown on a nearby display (Figure 2).

4.1.2. Protocol, measures and participants

At the beginning of the class in which the experiment was conducted, the construction process of LeCorbusier's Domino House was used to demonstrate different space concepts inside a solid form. After signing the consent form, participants used each techniques of the three. Before using a given technique, participants were shown how to create a void using that technique: taking apart the wooden blocks; making a cutting shape and using it as a template for a cut in FormZ; and sketching a command on the paper model surface using the CubeExplorer system. For each of the three techniques participants were given 40 minutes to complete the task .

We used two measures to compare the different techniques. First, after they finished the project, each participant was asked to fill out a questionnaire, providing a subjective evaluation of the three systems. The questionnaire covered topics such as ease of learning, ease of use, perceived efficiency while using the tool, as well as a self evaluation of how the tool helped participants to conduct the exercise. The questionnaire asked participants to rank the techniques side by side on each of these dimensions using a 1-7 Likert scale. The questionnaire took 10 minutes to complete.

We also asked two faculty in the department of architecture to rate the models produced during the experiment (in a unified file format and using randomized numerical identifiers). The criteria for evaluation were based on the three design goals described above (Section 4.1.1).

A total of nine students were divided into three groups of three participants with all members of a group using one technique at the same time (individually). We used a Latin square to counterbalance for skill transfer. Five of the participants had

commercial CAD experience (AutoCAD LC, SketchUp, Maya, etc.). Only one student had experience with digital pens, such as tablet PC styli. The experiment lasted 2.5 hours.

4.1.3. Results

One-way RM ANOVAs using the techniques as the independent variable were conducted to analyze questionnaire results. Bonferroni corrections were used for multiple comparisons and Greenhouse-Geisser corrections were used when sphericity could not be assumed. For the purpose of the analyses, data were recoded such that greater numbers are better. To account for experiment-wise alpha inflation, effects with significance levels above .003 (.05/17) should be interpreted with caution.

- *Ease of use:* We first examined the questions relating to general ease of use. For ease of getting started, we found a significant effect ($F_{(2,16)} = 14.43$, $p < .001$, partial $\eta^2 = .64$) suggesting that it was more difficult to get started with FormZ than with both wooden blocks and CubeExplorer ($p = .013$ and $p = .002$ respectively). A similar pattern was observed regarding the time spent learning ($F_{(2,16)} = 28.32$, partial, $p < .001$, $\eta^2 = .78$) with FormZ requiring more time than the other two techniques ($p = .002$ and $p < .001$ respectively). With respect to perceived mental load, we found a significant effect ($F_{(2,16)} = 20.8$, $p < .001$, partial $\eta^2 = .72$) suggesting that wooden block and CubeExplorer were significantly easier to use than FormZ ($p = .002$, and $p < .001$ respectively). In each of these analyses, the differences between CubeExplorer and wooden blocks were not significant. Finally, participants perceived CubeExplorer as faster and more efficient than both FormZ and wooden blocks ($F_{(2,16)} = 8.52$, $p = .003$, partial $\eta^2 = .52$, post hoc test $p = .026$ and $p = .004$ respectively). These results were consistent with informal observations during the experiment: It took a longer time for students to reach the level of comfort necessary to start their exploration in the FormZ condition as compared to the other two conditions.

- *Ease of Navigation:* From our observations, it seemed that it was quite difficult for participants to navigate with the wooden block technique because the cube assembly was difficult to move. However, self ratings showed no significant differences between the techniques. Also, there were no significant differences in the ease of observing the model as a whole or in visualizing the cut. It is interesting to note that while CubeExplorer requires users to manually align the 3D object with the virtual representation, this did not seem to influence the perceived ease of navigation. One reason suggested by students' comments was that CubeExplorer provides many views of the model – wire frame view, shaded view, and projection views of cutting objects on the paper surface. This could have offset the manual aligning burden.

- *Tool expertise*: We also asked participants how confident they were about their control of the tool. We found a weak but significant effect with regard to the ease of performing a simple cut ($F_{(1.17, 9.34)} = 5.52$, $p = .039$, partial $\eta^2 = .41$), with CubeExplorer being significantly better than FormZ ($p = .007$), but only marginally better than wooden blocks ($p = .062$). Interestingly, we did not observe a significant effect with regard to the ease of creating spatial overlap. Finally, we found a significant effect with respect to the ease of correcting simple errors ($F_{(2,16)} = 7.43$, $p = .005$, partial $\eta^2 = .48$) with CubeExplorer being rated

as significantly easier than wooden blocks (p = .014). With respect to the ease of making changes, CubeExplorer was significantly better than wooden blocks ($F(2,16) = 7.38$, p = 005, partial η^2 = .48, p = .014), but only marginally better than FormZ (p = .078).

- *Learning spatial concepts*: With respect to how well the tool supported the task, there were no significant effects observed from the questionnaire regarding the understanding of abstract space, how well the tool helped users convey their ideas, or whether the tool supported spatial thinking.
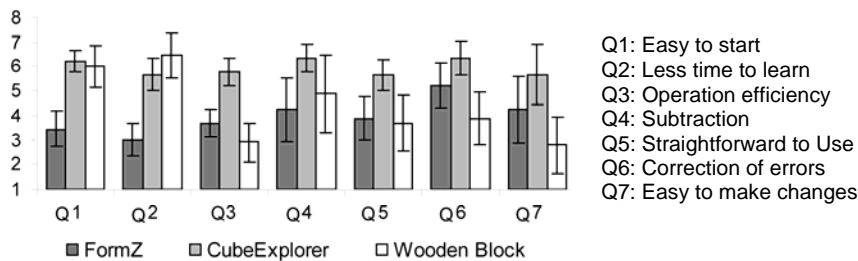
Figure 4 Experiment I, Questionnaire Results
Users rated each technique in 17 dimensions using Likert scale. 7 items showed significance. Higher values indicate higher satisfaction. Confidence levels (α =.05) are shown in error bars. CubeExplorer was easier to start, learn, and operate than FormZ. In terms of making modifications, it was more flexible than wooden blocks.

In terms of time allocation, the wooden block technique required a disproportionate amount of time to stack the component cubes, since the speed of an operation for wooden blocks is proportional to the total number of parts which have to be manipulated. The other techniques, in contrast, have constant times across operations. Hence, the total number of operations was likely lower in the wooden blocks setting. For the same reason, error correction was more difficult in the wooden block setting since it required repeated disassembly and reassembly. For CubeExplorer, adjusting the physical cubes to be aligned with the virtual cube on the screen was the most time consuming operation. For FormZ, as a consequence of the wide selection of operations, students had difficulty remembering the command set, increasing the time required.

Overall, the questionnaire findings – suggesting that CubeExplorer was rated as easy to start, quick to learn, efficient to operate, straightforward in subtraction, and efficient in correcting errors/making changes - confirm our first hypothesis that CubeExplorer combines the advantages of a tangible tool with the advantages of a digital tool. Interestingly, we didn't see any support for our second hypothesis that CubeExplorer is better than conventional tools at helping students develop conceptual clarity in spatial awareness. For the three design criteria described in section 4.1.1, the models generated with different techniques received almost identical ratings by faculty members. This is consistent with the lack of technique effects in the questionnaire responses regarding the "learning of spatial concepts" (see above).

4.2. Experiment II

In the first experiment, we used FormZ since it was well adapted to the task and also part of the curriculum at our university. However, it is clear that the interface of the CAD system could have influenced on the outcome of our experiment. For one, FormZ is a solid modeler, and different results could be obtained with a surface modeler such as SketchUp [3], which provides an intuitive interface to create the outline of a shape that users can elevate or depress to make a void. To identify the possible impact of this aspect, we conducted a follow-up study comparing the performance of CubeExplorer and SketchUp when used by novice users in a target matching task.

4.2.1. Task and apparatus

Each participant was given two wooden block models (see sample in Figure 1, left) and was asked to replicate them in a digital form using CubeExplorer and SketchUp. To allow for a fair comparison, users were allowed to use either an additive or a subtractive design approach. Assuming that most users would choose the additive approach for SketchUp and the subtractive approach for CubeExplorer, we selected one target model that was easy to replicate with subtraction and one that favored additive operations. Each participant built one model with each of the tools. The pairing between tool and model was counterbalanced across participants (i.e., half of the participants used SketchUp for the additive model and CubeExplorer for the subtractive model and vice versa). Also, half of the participants started with CubeExplorer and the other half with SketchUp.

In the SketchUp setting, each user was given a template file with preset grids and views. Users first defined a 2D sketch using either a rectangle tool or a line tool. Then, users subtracted or added volume using the "push/pull tool" controlled by the mouse. To simulate a 6"x6" grid system, the minimal snapping unit was set to one inch. Also, users were given a template file and a set of instructional guidelines to work with. The same version of CubeExplorer as in Experiment I was used.

4.2.2. Protocol, measures and participants

After informed consent, participants received a 5 minute overview of the general task. Before using each of the tools to replicate the target models, participants were trained for 20 minutes in the respective tool setting. During training, all possible strategies to shorten the task were fully disclosed. For SketchUp, we demonstrated how to use shortcuts and how to deal with a surface modeler's generic problems. For CubeExplorer, participants were trained to orient the sample and paper models efficiently. After the training, participants were asked to replicate the sample model as fast as possible.

The proficiency regarding each tool was assessed by the time users spent on replicating each model. Also, each participant filled out a subset of the questionnaire used for the previous experiment (i.e., the questions related to perceived expertise in using the tool).

Three architecture students and nine students without architecture training were recruited. No student had more than two days of SketchUp experience and none of the

participants had any experience with CubeExplorer. The total experiment took about 90 minutes with the last 10 minutes spent on evaluation.

4.2.3. Results

We conducted a one-way RM ANOVA using technique as the independent variable and completion time as the dependent variable. There was a significant effect of technique ($F(1,10) = 8.6$, $p = .015$, partial $\eta^2 = .462$) with CubeExplorer ($M = 5.5$ min, $SD = 2.2$ min) being faster than SketchUp ($M = 8.0$ min, $SD = 3.9$ min) .

This result may be explained by one of two aspects. First, there were frequent context switches among rotation, sketch, and push or pull using SketchUp. Second, as discussed above, SketchUp is a surface modeler. When users made two cuts that intersected in the middle, the definition of the inside/outside of the face frequently became inverted. Since the users of SketchUp had to manually fix the inverted and missing faces, this may have resulted in slower performance. If the SketchUp interface was implemented on top of a solid modeler, the result of the target matching experiment might have been very different. In addition, users adopted successful strategies to overcome the main drawback of CubeExplorer: The need to synchronize the paper cube with the virtual screen image. In this study, users focused on synchronizing the paper cube with the sample model instead of the virtual model on the screen. Thus, they spent less time trying to orient the electronic cube to align with the physical cube and this made operation very efficient.

On the questionnaire, the only significant effect was found for ease of learning ($F(1,11) = 12.91$, $p = .004$, partial $\eta^2 = .54$), suggesting that CubeExplorer was perceived as easier to learn ($M = 5.41$, $SD = 1.1$) than SketchUp ($M = 3.91$, $SD = 1.4$). None of the other differences reached significance.

In interpreting these findings, one needs to remember that this experiment focused on novice users working on a simple task. As a result, the external validity of the results might be limited and findings cannot be extended to expert users. Thus, findings are inconclusive regarding the relative performance of ModelCraft (i.e., the "expert" version of CubeExplorer) versus the full SketchUp program.

5. Discussion

Based on our observations as well as interviews with the students, we conclude that three key elements of CubeExplorer are beneficial in introductory architecture classes.

First, the *directness of interaction* supported by CubeExplorer was beneficial for students performing the Cube Project. In comparison to the digital modeler, use of a physical model and a digital pen brought the editing metaphors in the electronic model to the tangible world, making the students perceive the interface as "easy to use." In comparison to the physical model, although physical blocks are very intuitive to operate, users have to consider stability issues when stacking and removing component blocks one by one to try out different compositions. Additionally, the operations in a physical model are not performed in the order in which students conceptualize projection and this is a key element in learning 3D spatial concepts. In contrast, the interactions in CubeExplorer allow users to sketch points, lines, depth

marks, and 2D shapes in the correct conceptual order. This allows the user to attend to one attribute of a geometric component at a time [8]. More importantly, the operations in CubeExplorer were simple enough that the system configuration interfered minimally with the purpose of training students in the concepts of composition of void space.

Second, the *unique self-referential system* of CubeExplorer allowed the system to receive high satisfaction rates in navigation and visualization. In comparison, when using wooden blocks, gravity limited the exploration pattern because it implicitly created a "ground" plane. Users of FormZ, in turn, were constrained by the Cartesian system that is deeply coupled with most of the functions of CAD systems. For example, users are asked to abide by the reference system of the internal XYZ axes to assign input parameters for certain operations, although they can view the object from an arbitrary vantage point. In contrast, CubeExplorer allows users to use the natural reference of their cuts, i.e. the face they are drawing on.

Third, as a hybrid interface, CubeExplorer *combines the advantages of physical and digital media*: Like physical tools, the interface is easy to use; like digital tools, modifications and undo operations are simple to execute. The hybrid visualization, consisting of the physical cube and the representation on screen, provides a direct spatial view and a variety of geometric views in digital form. Our second experiment reinforces the benefits of CubeExplorer in comparison to digital modelers by demonstrating that students can produce designs as comfortably with CubeExplorer as with purely-digital tools such as SketchUp.

However, we also observed several technical problems with CubeExplorer during the user studies. The ink that was laid on top of the paper face while executing an operation was useful at the time of the execution. However, after using the paper palette to delete a previously created feature, the residual ink confused the users. In addition, since every face was symmetric, users frequently had to reorient either the paper model in accordance to the digital model on the screen or vice versa. In short, CubeExplorer had several sources of inconsistency between the tangible model and the digital model. In future versions, this synchronization issue could be resolved by utilizing camera tracking to detect the position and rotation of the paper model and send it to the digital modeler.

6.   Conclusion

In this paper, we present CubeExplorer, a tangible user interface for an introductory architecture class. CubeExplorer is designed to let students explore components of 3D spaces such as projection, overlap, and void. Users can draw on the surface of physical models to trigger operations in a CAD program running on a nearby computer and this minimizes the level of indirection between the intended operation and the manipulation tool. To evaluate the potential of CubeExplorer, we conducted two experiments comparing it to a purely physical system as well as two digital applications (FormZ and SketchUp). Our results show that the key elements of the CubeExplorer interface - directness of interaction, a unique referential system, and simultaneous advantages of physical and virtual modeling tools – cannot be obtained from conventional tools in architecture. We believe that the concepts explored in

CubeExplorer could be applied to a wide variety of tangible interfaces both in teaching and professional contexts.

Acknowledgements

References

1. AutoCAD AutoDesk www.autodesk.com.
2. FormZ 2005, Auto-des-sys www.formz.com.
3. @Last Software, SketchUp. 2005.
4. Anderson, D., J.S. Yedidia, J.L. Frankel, J. Marks, A. Agarwala, P. Beardsley, J.H.D. Leigh, K. Ryall, and E. Sullivan. Tangible interaction + graphical interpretation: a new approach to 3D modeling. *Proceedings of SigGraph'00*, pp. 393-402.
5. Anoto, Development Guide for Service Enabled by Anoto Functionality. 2002, Anoto.
6. Arvo, J. and K. Novins. Fluid sketches: continuous recognition and morphing of simple hand-drawn shapes. *Proceedings of UIST'00*, pp. 73-80.
7. Frazer, J., *An Evolutionary Architecture*. Themes; 7. 1995, London: Architectural Association.
8. Goel, V., *Sketches of Thought*. 1995: MIT Press.
9. Igarashi, T., S. Matsuoka, and H. Tanaka. Teddy: a sketching interface for 3D freeform design. *Proceedings of SigGraph'99*, pp. 409-416.
10. Masry, M., D. Kang, and H. Lipson, A Pen-Based Freehand Sketching Interface for Progressive Construction of 3D Objects. Computer & Graphics, 2005. **29**: p. 563 - 575.
11. Piper, B., C. Ratti, and H. Ishii. Illuminating clay: a 3-D tangible interface for landscape analysis. *Proceedings of CHI'02*, pp. 355-362.
12. Sharlin, E., Y. Itoh, B. Watson, Y. Kitamura, S. Sutphen, and L. Liu. Cognitive cubes: a tangible user interface for cognitive assessment *Proceedings of SIGCHI'02*, pp. 347-354
13. Shneiderman, B. and C. Plaisant, *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. 4th ed. 2004: Addison Wesley.
14. Song, H., F. Guimbretière, H. Lipson, and C. Hu. ModelCraft: capturing freehand annotations and edits on physical 3D models. *Proceedings of UIST'06*, pp. 13 - 22.
15. Suzuki, H. and H. Kato. Interaction-Level Support for Collaborative Learning: AlgoBlock. *Proceedings of An Open Programming Language. In Proceedings of CSCL*, pp. 349-355.
16. Underkoffler, J. and H. Ishii. Urp: a luminous-tangible workbench for urban planning and design. *Proceedings of CHI'99*, pp. 386-393.
17. Watanabe, R., Y. Itoh, M. Asai, Y. Kitamura, F. Kishino, and H. Kikuchi. The soul of ActiveCube: implementing a flexible, multimodal, three-dimensional spatial tangible interface. *Proceedings of ACE'04*, pp. 173-180.
18. White, J.F., G. Sadek, J. Hejduk, and E. Shaw, *Education of an Architect*. 1971: The Cooper Union for the Advancement of Science and Art.
19. Wisneski, C., H. Ishii, A. Dahley, M. Gorbet, S. Brave, B. Ullmer, and P. Yarin, Ambient Displays: turning architectural space into an interface between people and digital information, in *Cooperative Buildings. Integrating Information, Organization, and Architecture. First International Workshop, CoBuild'98 Proceedings*, N.A. Streitz, S. Konomi, and H.J. Burkhardt, Editors. 1998, Springer-Verlag: Berlin, Germany. p. 22-32.
20. Zeleznik, R.C., K.P. Herndon, and K.P. Herndon. SKETCH: an interface for sketching 3D scenes. *Proceedings of SigGraph'96*, pp. 163-170.
21. Zuckerman, O., S. Arida, and M. Resnick. Extending tangible interfaces for education: digital montessori-inspired manipulatives. *Proceedings of SIGCHI'05*, pp. 859-868.