"Seeing Solids" via Patterns of Light: Evaluating a Tangible 3D-Input Device

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ABSTRACT
This paper describes pilot tests of a prototype device for 3-dimensional input called the *UCube*; briefly, this device permits spatial input to be conveyed "by hand", by turning on (or off) elements of a volumetric array of lights whose positions are then sent to a desktop computer. The purpose of the UCube is to allow users–especially students and novices with little experience of 3D design–to create a wide variety of three-dimensional shapes without the need for complex modeling software. In this paper, we describe tests of the UCube with middle-school students, focusing on the ability of students to visualize and model solid forms employing the device. We use the results of these pilot tests to ground a wider-ranging discussion of (a) how the device itself might be further developed, and (b) more general issues in designing systems for interactive three-dimensional input and fabrication.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User interfaces-graphical user interfaces.

General Terms
Design, Experimentation, Human Factors.

Keywords
UCube, 3-dimensional design, child-friendly design, tools for fabrication.

1. INTRODUCTION
This paper describes systematic pilot tests of a prototype device, called the *UCube*, intended to provide a means for natural, "body-centered" 3D input. The UCube has been the subject of an earlier report [5] in which we focused on its use as an educational device for students, and as an input device for the description of solid polyhedral forms for 3D printing. The focus here is on a recent set of pilot tests that we conducted to evaluate the usability of the device for 3D visualization and modeling. By reflecting on the results of this study, we can in turn provide potentially fruitful research suggestions for those interested in designing systems that employ 3D thinking and fabrication. The remainder of this paper is as follows: we provide a very brief system overview of the UCube, followed by the procedure, results, and discussion of the aforementioned pilot study. We conclude with a discussion of how our device fits into the larger conversation surrounding educational technologies for fabrication.

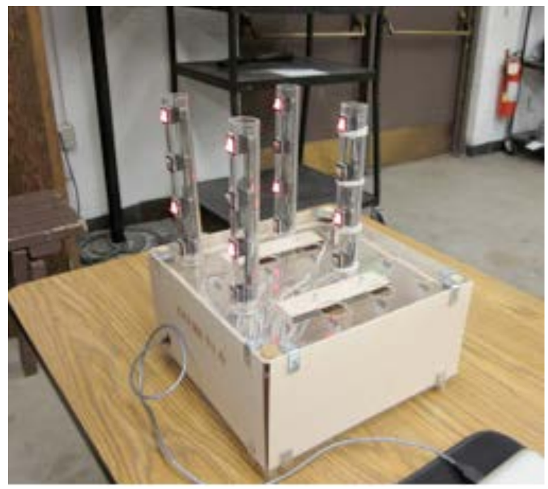

Figure 1. The *UCube* system, shown here with four of a possible 16 towers in place, with two lighted switches on each tower, together indicating the 8 vertices of a cube "2 units" in size.

2. THE UCUBE: A BRIEF SYSTEM OVERVIEW
The photograph in Figure 1 indicates the basic design of the UCube platform itself. The device can be described as follows: it is a platform with an array of holes into which tall cylindrical towers (of transparent plastic) may be inserted. Each of the towers is equipped with a series of lights, spaced at equal intervals along the tower. By placing towers into selected holes within the platform, and by turning on individual lights, one can select specific points in a region of three-dimensional space. The arrangement of these selected points can then be input to a desktop computer, providing "3D input" without the use of anything more than one's hand and eye for guidance. In the Figure 1 photo, the user has placed four towers into the platform; the four towers are at the corners of a square whose side-length (as measured in "hole-intervals") is 2, thus the entire set of points may be looked at as a cube of size 2. Users may also manipulate, perturb (off the integer lattice), load, save, and 3D-print the shape from the UCube software. Again, a more detailed account of system operation may be found in [10].

3. USER STUDY

Early in 2012, we conducted a user study of the UCube with a group of 11-13 year olds. The group consisted of ten participants, eight boys and two girls, from a local middle school multimedia class. Every participant was individually led through two separate exercises (outlined below) using the UCube.

3.1 Procedure: Modeling

Participants were handed a 3D-printed shape (modeled and printed from the UCube) and were instructed to attempt to model the shape using the UCube. The participant was initially allowed to hold the shape for approximately 10 seconds, after which they would hand the shape back to the facilitator and attempt to model the shape from memory. Participants were instructed that they may ask to hold the shape again, at which point they were allowed to hold it throughout the duration of the modeling task. Additionally, users were instructed that they had the option to skip a shape and return to it at a later point in the exercise.

The five physical shapes presented were: a cube, a tetrahedron, a diamond, a 'house' (a cube with a pyramid on top), and a complex irregular polyhedron. The models were presented to the user starting with the cube (as this was deemed to be the most basic shape with regard to modeling complexity). To avoid an ordering bias, we randomized the presentation sequence of the next four shapes using an online random order generator. If, after skipping a shape and returning to it, the participant was still having difficulty, we offered them the opportunity to attempt modeling the shape with the help of the UCube software, the effects of which are discussed in the results section. Participants were given a total of 25 minutes for the modeling exercise. We recorded, but did not limit the modeling time per shape, only the total time for all five shapes.

3.2 Procedure: Matching

Participants were instructed to face away from the UCube while the facilitator modeled a set of lights on the UCube corresponding to one shape among a set of physical models laid out on the table next to the UCube. Once the lights on the UCube were set up, the participant was instructed to turn around, and indicate which physical object they thought the set of lights on the UCube corresponded to.

There were nine physical models presented on the table, and consisted of a cube, a tetrahedron, the 'house' shape, a diamond, a triangular prism, an elongated hexagon, a parallelogram, a trapezoid, and an irregular polyhedron (see Figure 2 for all the models). The shapes were always presented on the table in the same order and orientation to avoid discrepancies in perception or association.

Of the nine shapes, the participants were asked to match five of them (the cube, the triangular prism, the parallelogram, the elongated hexagon, and the trapezoid). Thus, only the cube was presented in both the matching and modeling exercises. As with the modeling exercise, the cube was presented first, with the remaining four shapes presented in a computer-generated randomized order.

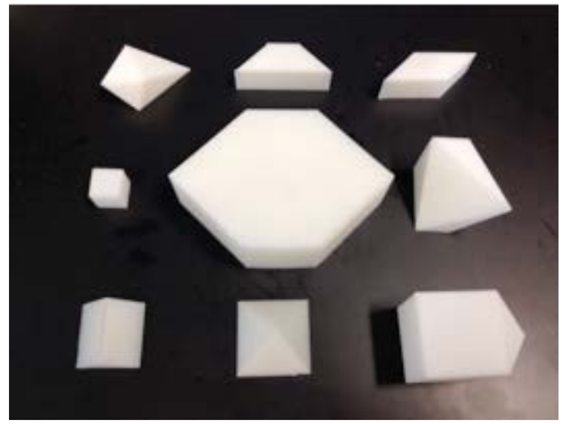

Figure 2. The nine models used during the user study: (by row, from top left) diamond, trapezoid, parallelogram, cube, elongated hexagon, irregular polyhedron, triangular prism, tetrahedron, house.

Participants were given a total of ten minutes for the matching exercise, corresponding to two minutes per shape, and were instructed to think aloud during the process.

4. RESULTS

While many established forms of 3D modeling systems can be confounding and operationally too complex for a child to navigate, the UCube was positively received and system instruction was accomplished with just a minor introduction and demonstration (system instruction and demonstration lasted approximately 2-3 minutes). We found this first instance of system comprehension to offer some validation that the UCube worked well as a user-friendly 3D modeling device. This section will detail the outcome of both the modeling and matching tasks performed.

4.1 Exercise 1: Modeling

Modeling occurred under three conditions: recreate the object from memory, construct the object while it was in the participant's possession, and model the shape with the help of the UCube software. Overall, 21 of 50 shapes were completed from memory, 12 of 50 were completed while holding the shape, and a further 8 of 50 were completed with the aid of the UCube software, for a total of 41 out of 50 shapes modeled successfully (82%). Of the nine missed shapes, seven were of the same shape, the complex polyhedron. The remaining two misses were from the same participant, who ran out of time before completion.

Of the 10 participants, 8 were able to recreate the cube from memory, whereas only 4 were able to recreate the diamond and the tetrahedron from memory. Half of the participants constructed the house from memory, and no participants were able to complete the irregular polyhedron from memory. However, once shown the software the majority of the participants found the modeling task significantly easier to perform. The irregular polyhedron was by far the hardest shape and was only able to be completed by 3 of the 10 participants either after continued possession of the shape or using the software.

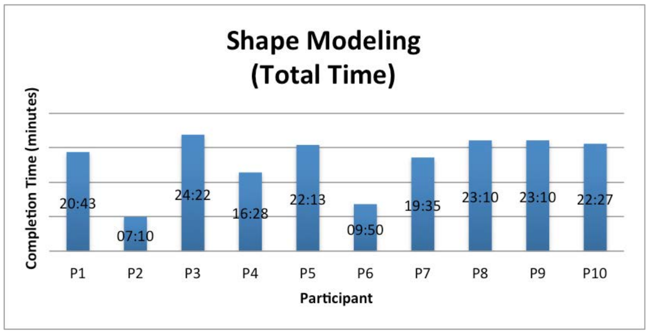

Table 1. Total time per participant for the modeling task.

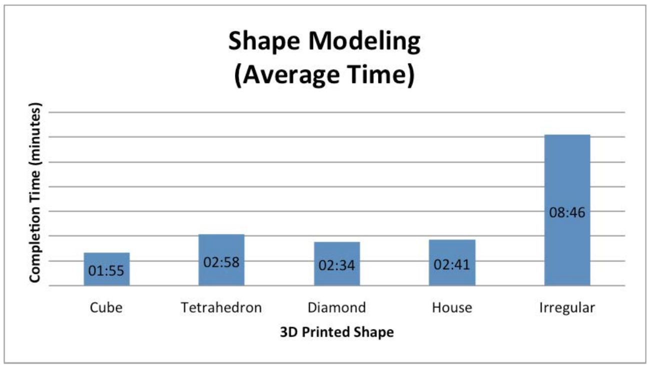

Table 2. Average time per shape for the modeling task.

Table 1 and Table 2 represent the total completion times per participant and average time per shape, respectively. Two exceptional completion times were observed, where participants finished modeling all the shapes in under 10 minutes. However, the majority of participants finished the task in the 19-25 minute range. Only one of the participants ran out of time. Once participants had been introduced to the software, ninety percent of participants were able to complete all but the irregular polyhedron. It is interesting to note that of the 10 participants, the child that had the most difficult time modeling, the lowest shape completion rate, and the longest completion time during the matching exercise was the youngest participant.

4.2 Observations

Modeling trends as well as distinct modeling behaviors were documented in the process. Common observations included building from the ground up (lowest vertices first), building in the orientation that the object had been presented in, not clearing the poles/lights from the UCube before starting to model a new shape, and modeling a shape by breaking it up into discrete parts (e.g. a participant building a house would commonly build a cube first and then add on a vertex to the top; a participant constructing the diamond might combine two opposite facing triangles.).

Unique behaviors were exhibited in the modeling process as well, reflecting a type of user-specific construction-based problem-solving. One participant used their arm to connect the red lights of the UCube for shape definition. A few participants oriented the object differently than how it had been presented–typically this occurred for the modeling of those objects with a pyramidal apex (tetrahedron, house, diamond). Apex formation was perhaps one of the most difficult concepts for most participants to grasp, as it required them to strategically align the base on a 3x3 grid so there was a middle plug for them to create the apex. If participants were fixated on designing from a 4x4 grid then there was no center plug for them to create a midpoint. Some participants ended up building an oblong polyhedron as opposed to a cube, or an oblique polyhedron as opposed to an equilateral tetrahedron. Other observed behaviors included a participant who modeled shapes by turning on lights for an entire shape edge, as opposed to just the corners and a participant who built shapes that were floating, as opposed to resting on the base of the UCube.

There were also some notable behaviors regarding physical and gestural actions of the participants. Many participants modeled with both hands simultaneously, placing towers and flipping switches without a clear preference for a dominant hand. Participants would often gesture with their arms following an arc in parallel with a face of the object they were currently modeling. This 'tracing' behavior was also noticed when participants were holding a physical model and tracing a side of the object with their fingertip, often while rotating the object with the other hand. Finally, during object possession phase three participants actually placed the 3D object on top of the UCube in the modeling space while they reasoned out the construction (see figure 3 for an example).

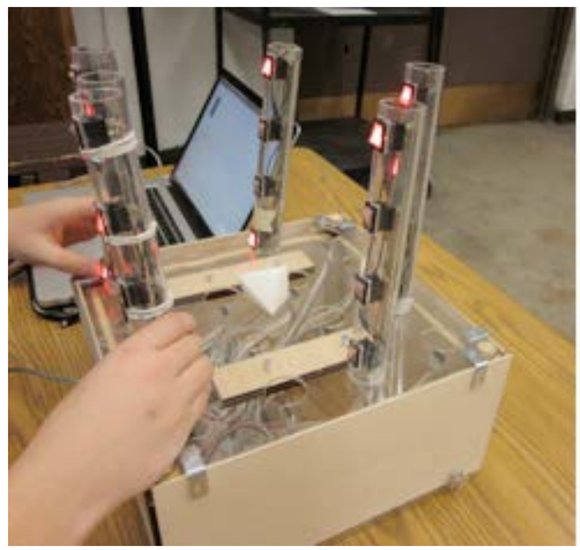

Figure 3. A participant modeling with the UCube, using a strategy of placing the physical model on top of the UCube while modeling, as well as using both hands simultaneously to manipulate the towers.

4.3 Exercise 2: Matching

Out of 50 matching tasks (five per participant), all but three tasks were completed in 20 seconds or less. Table 4 displays the average completion times for each shape. No participant selected the wrong shape (a few preliminary 'mis-selections' were made that the participants quickly corrected), and all participants completed the task in well under the allotted 10 minutes.

The lack of errors in the matching task is highly encouraging as a basis from which to reason about youngsters' abilities to perceive and reason about convex hulls as a set of lit vertices in space, meaning that this kind of 3D modeling interface might be applied to other domains (e.g., as a cognitive assessment tool, a puzzle game, etc.) with some optimism.

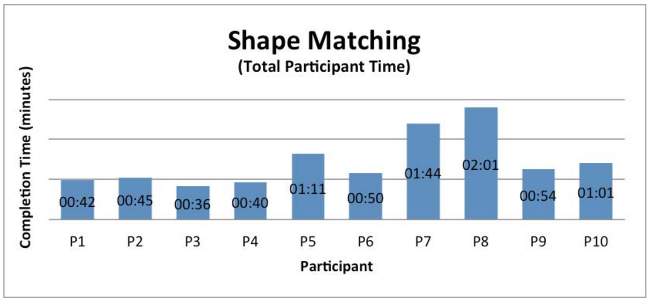

Table 3. Total time per participant for the matching task.

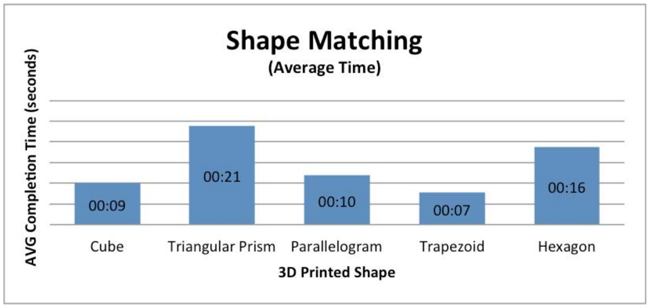

Table 4. Average time per shape for the matching task.

5. RELATED AND INFLUENTIAL WORK

Several ongoing lines of research influenced the creation of the UCube. We have already mentioned, in passing, several projects focused on the area of 3D input. Our own emphasis (as indicated by our choice of test subjects) has been in the design of 3D interfaces suitable for use by children, particularly in the context of 3D fabrication; that is, we wish to make it easier for youngsters to exploit the remarkable world of accessible devices for printing out objects in plastic and other materials. In this area, we have been particularly influenced by researchers who have looked at the relationship between "embodied cognition" and mathematical understanding–an idea famously championed by Papert [7], and more recently revived in the texts by Lakoff and Nuñez [4] and Goldin-Meadow [3]. More recently, research by Abrahamson and his group has focused on the design of physical devices to support "embodied mathematics" [cf. 1], while Arzarello and Edwards [2] introduce a provocative set of research papers illustrating the increasing role of gestural study in mathematics education.

Our design of the UCube has been in response to this tradition of incorporating bodily knowledge within mathematics education. Importantly, however, we do not see the UCube purely as a *pedagogical* device (e.g., to teach 3D coordinate geometry), although it might well be useful for that purpose. Rather, we see the UCube as an interactive device to aid children (and novices) in *expressive* or *constructive* activities that happen to be informed by mathematics. In this sense, we are also influenced by Papert's notion of "constructionism" (cf. [9] and the introductory discussion in [6]).

6. SUMMARY; ONGOING AND FUTURE RESEARCH

As the results of the study were promising, we are continuing with development of the UCube, producing a more expressive physical interface with 7x7x7 points and multi-color (thus multi-player) interaction. We believe that the study described here points toward a fertile interplay between the design of novel devices and systems for 3D modeling and a better understanding of spatial cognition and reasoning. We believe that the design of interactive tools such as the UCube can not only provide an easier introduction to creative fabrication for children, but can suggest promising new directions for "spatial education" in mathematics, engineering, the sciences, and the visual arts.

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