Designing Interactions for 3D Printed Models with Blind People

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ABSTRACT

Three-dimensional printed models have the potential to serve as powerful accessibility tools for blind people. Recently, researchers have developed methods to further enhance 3D prints by making them interactive: when a user touches a certain area in the model, the model speaks a description of the area. However, these interactive models were limited in terms of their functionalities and interaction techniques. We conducted a two-section study with 12 legally blind participants to fill in the gap between existing interactive model technologies and end users' needs, and explore design opportunities. In the first section of the study, we observed participants' behavior as they explored and identified models and their components. In the second section, we elicited user-defined input techniques that would trigger various functions from an interactive model. We identified five exploration activities (e.g., comparing tactile elements), four hand postures (e.g., using one hand to hold a model in the air), and eight gestures (e.g., using index finger to strike on a model) from the participants' exploration processes and aggregate their elicited input techniques. We derived key insights from our findings including: (1) design implications for I3M technologies, and (2) specific designs for interactions and functionalities for I3Ms.

CCS Concepts

• **Human-centered computing~Participatory design**

Keywords

Interactive 3D printed models; visually impairments; exploration behaviors; elicitation

1. INTRODUCTION

Recent developments in 3D printing technologies have made 3D models much more available to blind people. With relatively affordable, consumer grade 3D printers, teachers and blind students can print tactile models at schools and their homes [6]. In addition, "makers" around the world [10], DIY hobbyists who use 3D printing and other rapid prototyping technologies, have shared millions of 3D printable models online. Such models include architectural structures, cartoon figures, human organs, and many others. These models can help blind people learn complex concepts (e.g., the structure of a molecule) that cannot be conveyed from text alone.

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Figure 1. The eight gestures identified in the Elicitation section of the study. The movements of dynamic gestures are marked with arrows.

Seeing the potential of 3D models, researchers have developed methods of enhancing them by augmenting them with audio descriptions. They created interactive 3D printed models (I3Ms) with sensors like cameras [25, 31], capacitive sensors [9, 17, 38], and microphones [30, 32]. These interactive models can sense a blind user's gestures and speak corresponding audio information to the user. However, prior work focused on the technical aspects of sensing input on the models and producing output; no work has investigated the methods and behaviors of blind people as they explore tactile 3D models and determined their needs for interactivity. To date, most I3Ms supported straightforward interactions designed by researchers (e.g., pointing to a continent on a globe model to get its label). These designs didn't fully explore the design space and power of I3Ms.

In this paper, we aim to understand blind people's needs and preferences for the design of interactivity in 3D printed models. Specifically, we investigate two research questions:

RQ1: How do blind people explore tactile models (that are not interactive)?
RQ2: What interaction techniques are effective in I3Ms?

Answering both questions is critical to our aim. I3Ms are a new medium that present undiscovered design opportunities. Unlike designing interactions for traditional web browsers [23] or desktop systems [42] that have established functionalities, interaction design for 3D printed models is not established and we do not yet know what functions are needed or useful. The goal of interactive systems is to support and adapt to users' behaviors [8], rather than the opposite. Thus, RQ1 contributes to the fundamentals of I3Ms, while RQ2 takes a direct action to seek interaction techniques for I3Ms.

To answer the questions, we conducted a two-section study with 12 legally blind participants. In the first section of the study, we observed participants as they performed several tasks to explore and identify 3D printed models and their components (RQ1). In the second section of the study, we elicited interactions from participants [42], asking them to define input techniques for five interactive functions for an I3M (RQ2). We used three models throughout the study: a globe, a cell, and a map.

Our findings reveal that 3D model exploration involves five major types of exploration activities (e.g., counting similar tactile elements), four hand postures (e.g., using one hand to hold a model on the table), and eight gestures (as seen in Figure 1). In the second section of the study, participants suggested touch gestures on the model, speech commands, and buttons to trigger interactive events. We conclude with a design for I3Ms along with implications for future I3M technologies.

In summary, our contributions include:

(1) An in-depth analysis of blind people's exploration behaviors of 3D printed models.
(2) A set of user-defined input techniques for various I3M functionalities.
(3) Design implications for I3Ms and a specification for an I3M system.

2. BACKGROUND AND RELATED WORK

2.1 3D Printing

3D printing technology is becoming more and more available. 3D printers have evolved from pieces of industrial equipment to personal tools, and are widely used in fabrication activities like prototyping and repairing [20]. People can already print tools and models with printers found in community maker spaces, schools, and libraries. Some printers cost as little as $100 [41].

Researchers have created printable content to help people with disabilities solve their own accessibility problems. People have designed specialized devices for prosthetics users [13] and people with motor and mobility impairments [5]. For blind people, personal printers can create tactile learning materials that benefit blind people in education. Prior work designed 3D printed graphics to help blind people learn programming [14], design [21], mathematics [3, 6], and basic literacy skills [15, 34].

As 3D printing technology continues to evolve, blind people will be able to print models at home, at school, or at their local library. Our work aims to make these printed models more powerful, by understanding how researchers and designers can add interactive elements to best address blind people's needs and preferences.

2.2 Interactive 3D Printed Models

Accessibility researchers have explored different methods to create I3Ms. Equipped with sensors, these I3Ms can sense a blind user's gestures and provide audio feedback to the user.

Shi *et al.* [32] used acoustic sensing to add audio labels to 3D printed models. To add a label, a designer added a printable percussive component called a "Ticker" to the model that could be strummed with a flick of the finger. Each ticker generated a unique sound that was then detected by a mobile application. The application would then speak the label associated with the strummed Ticker. In a user study with nine blind participants, the application classified Ticker sounds with a mean accuracy of 93 percent, and participants enjoyed using the application.

Another approach to adding interactivity to a 3D printed model is to embed conductive filament into the model. When a model is placed on a touchscreen, users can touch the conductive parts of the model to trigger inputs on the touchscreen. In this way, audio information can be associated with touches on the model that are sense by the capacitive sensor. Kolitsky [17] and Taylor *et al*. [38] used this technique to add audio labels to printed tactile graphics and maps. Similarly, LucentMaps [9] combined this technique with speech input to make printed maps more accessible to visually impaired people. LucentMaps provided both audio and visual feedback to explain and highlight elements in printed transparent maps.

Computer vision has been applied to I3Ms as well. Reichinger *et al.* [25] used a depth sensor to allow blind people to explore tactile reliefs with audio guidance. They designed three gestures to retrieve audio labels, get detailed audio descriptions, and turn on or turn off audio feedback on tactile reliefs. CamIO [29] and our previous work [31] also used similar approaches to add audio labels for 3D models.

This growing number of accessibility research indicates the importance of I3Ms to blind people. However, prior work mostly focused on the technical challenges of creating I3Ms, and these systems only had straightforward interactions designed by researchers. Our study contributes to I3M design by understanding users' behaviors and needs, and eliciting interactions f them.

2.3 Tactile Perception

Tactile perception consists of cutaneous perception and haptic perception. According to Hatwell *et al.* [1] [12], cutaneous perception perceives information using the skin in a stationary process. Haptic perception, on the other hand, involves moving one's muscles and the whole shoulder-arm-hand system. People use tactile perception to sense temperature, shape, texture, pressure, vibration, and pain.

Prior work has studied the exploration process and object properties that people use to identify an object. Lederman *et al.* [19] defined Exploratory Procedures (EPs) as stereotyped movement patterns that do not correspond to any configuration of the hand or gesture. They found participants performed different EPs to examine a specific property of a 3D object (e.g., performing static contact EP to examine temperature, while performing pressure EP to examine hardness). Klatzky *et al.* [16] further confirmed three properties contributed to tactile object identification: the material, the size, and the shape of an object. Both studies were conducted with sighted participants.

Compared with sighted people, blind people used different strategies in tactile perception tasks. Previous studies suggested that blind participants preferred to use two hands and multiple fingers, while sighted participants usually chose to use one hand with only one or two fingers in tactile perception tasks [7, 26, 35]. Also, researchers found that blind participants completed tactile perception tasks with higher accuracy and at a faster speed than sighted participants [7, 22, 26].

Unlike traditional tactile objects, 3D printed models are unique learning tools. Perceiving information from printed 3D models is a more complex task than the tactile perception tasks performed in the work mentioned above. Although prior work yielded us insights about tactile perception, no prior research has examined blind people's experiences when interacting with 3D printed models. We aim to fill this gap by understanding blind people's exploration behaviors on 3D printed models. Our study highlights the major activities, hand postures, and gestures blind people used, which sheds light on the design opportunities for I3Ms.

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[1] There are different definitions for haptic and cutaneous perception. We used the one introduced by Hatwell *et al.* [12].

3. STUDY DESIGN

3.1 Study Objectives

We aim to draw design implications from (1) blind people's exploration behaviors of 3D printed models and (2) user-defined input techniques. Thus, we conducted a two-section study to answer the two research questions posed in the introduction.

3.2 Participants

We recruited 12 legally blind participants (4 males, 8 females) whose ages ranged from 23 to 60 years (mean = 40.75, SD = 13.15). Eleven participants identified as blind, while the remaining one identified as low vision. Eight participants had a college or graduate degree, and four participants had only graduated from high school. Eleven participants were familiar with Braille, but four of them didn't read it regularly. Eleven participants had iPhones, while the remaining one did not use a smartphone. We compensated each participant 15 USD per hour and reimbursed transportation expenses up to 60 USD.

3.3 Procedure

The study consisted of one session that was about 60 minutes long. The session included two sections, which we refer to as *Exploration* and *Elicitation*[2]. After introducing the project to a participant, we began the Exploration section, in which we asked them to explore three models by performing three tasks. Then, we began the Elicitation section. In a typical elicitation study, researchers prompt a user with the effects of an action, known as *referents*, and the user is expected to provide the causes of the action, known as *signs* [8]. In our study, we asked users to define signs (input techniques) for six Referents (functions) with the three models.

We designed tasks for the Exploration section that would prompt participants to both explore the models as a whole and examine smaller model components. Hatwell [11] and Lederman *et al.* [18] found that exploration using tactile perception involves two stages: an overview and detailed exploration; participants would stop exploring at the first stage if no further instruction was given. Thus, our three tasks were:

Task 1. *Identify the Model.* We asked participants to tell us what the model represented. If a participant didn't know what the model was, the researchers told her.

Task 2. *Describe the Shape of an Element.* We asked participants to describe a designated element on each model: Nucleus in the Cell model, North America in the Globe model, and the round building in the Map model. If a participant couldn't find the specific element, the researchers showed her the location of the element.

Task 3. *Describe the Shapes of Nearby Elements.* After Task 2, we asked the participant to explore and describe the elements near the designated element from Task 2.

When performing the tasks, we asked participants to think aloud and explain what they were feeling and doing. If they asked questions about the content on the models, we would answer them after they finished the tasks. We gave the participant one model at a time, and counterbalanced the order in which the models were presented with a Latin triangle. The Exploration lasted around 20 minutes, and participants were encouraged to take a break after finishing each model.

During the Elicitation section, we invited participants to design input techniques they wanted to use to get audio output from I3Ms. We used the same models we used during Exploration, and asked each participant to define input techniques for six functions, henceforth referred to as referents. The first four referents were demonstrated in interactive printed maps [9, 38]. The last two referents were discussed by Shi *et al.* [32]. All referents used audio as feedback. These referents included the following, with examples from a globe model:

Referent 1. *Get General Model Information.* The system provides a high-level description of a model: "this is a globe with seven continents."

Referent 2. *Select an Element and Get its Name.* the user selects a continent and the system speaks its name: "North America."

Referent 3. *Select a Sub-Area of an Element and Get its Name.* The user selects an area on North America and the system says: "This is where the Rocky Mountains are."

Referent 4. *Get More Information.* The system provides information about the Rocky Mountains from Wikipedia.

Referent 5. *Record Notes.* The user performs a technique to record notes about the Rocky Mountains.

Referent 6. *Retrieve Notes.* The system speaks the previously recorded notes about the Rocky Mountains.

As is standard with elicitation studies [42], we went through each referent with a participant and asked her to elicit input with the help of Wizard-of-Oz audio feedback. We prompted her by saying "If the models can sense your behaviors and understand your speech, how would you like to interact with the models?" Then, a researcher demonstrated the audio output for each referent. For example, when demonstrating Referent 1 for the Globe model, the researchers used a script to produce synthesized speech for the sentence: "This is a globe model. You can find Asia, North America, South America, and Africa in this model." After demonstrating all referents, the participant was asked to design input techniques to trigger these referents. When the user performed a possible input technique, the researcher played the audio output to simulate the complete interaction.

For each referent and each model, participants were asked to define one input technique. They could use the same inputs for the three models. If they felt that one of the referents was unnecessary for a given model, we allowed them to skip this referent. As with the Exploration section, we gave each participant one model at a time, and counterbalanced the order in which the models were presented with a Latin triangle.

3.4 Apparatus and Materials

We printed three models for the study. We downloaded these models from Thingiverse and OpenStreetMap Buildings [24], online 3D maps containing the models of building geometries. Since most interactive models require auxiliary components (e.g., visual trackers [29]) to sense users' touches, we added a stick to the top of each model to represent an auxiliary component, as shown in Figure 2. The models were printed on a Makerbot 5th generation printer. The three models included:

[2] We used "elicitation" instead of "gesture elicitation" to include other modalities in addition to gestures.

1. *Cell*: A cell model modified from thing: 689381 [1]. The model has a Nucleus, two Golgi Apparatuses, three Mitochondrion, and four semi-spheres representing Peroxisomes.
2. *Globe*: A globe model modified from thing: 17336 [40]. The model has seven continents.
3. *Map:* A map model downloaded from OpenStreetMap Buildings. The model includes several buildings.

We developed a Python script that used the text-to-speech engine in a Macbook to speak texts, which provided Wizard-of-Oz audio feedback.

3.5 Analysis

We used two cameras to record the study: a fixed camera mounted on the table and a hand-held camera operated by a researcher. Two researchers analyzed the videos recorded by two cameras.

We analyzed the video data from the Exploration section in three stages, following Lederman *et al.*'s video coding method [19]. This method allowed us to combine data from our observations of participants' behavior and their reported thought process. In the first stage, we carefully reviewed the videos from the hand-held camera, and coded them using digital note cards. A note card contained a static frame from the video, an identification code, and text explaining this frame and related dialog from the video. A researcher initiated the transcription process by creating a series of note cards for a video clip. Then the other researcher validated the note cards to make sure the cards represented the video clip.

In the second and third stages, two researchers categorized the note cards into themes in an iterative process. In the second stage, the researchers printed the note cards, and clustered them into several groups based on the performed hand postures and gestures described in the note cards, as shown in Figure 3. Then, they identified themes, like common exploration activities and questions participants asked about the models. In the third stage, the researchers independently reviewed each note card with the identified themes, and validated the themes. We collected and coded a total of 300 note cards.

For data from the Elicitation section, we sorted suggested input techniques, and transcribed only the audio data of the videotapes. We calculated the Max-Consensus and Consensus-Distinct Ratio for each Referent, following Morris *et al.*'s approach [23]. We developed themes from the transcription using axial coding [27].

4. FINDINGS: EXPLORATION

We describe the findings from the Exploration section of our study. We found that participants performed five distinct exploration activities, frequently used four hand postures, and performed eight gestures during the exploration tasks.

4.1 Exploration Activities

When a participant explored a model, she sensed the texture and shape of the model, measured the size of the elements, counted the number of elements, compared similar elements, and communicated with the researcher. In the study, these activities appeared in all three tasks, including Task 2 and 3 where participants could complete the tasks by only sensing the texture of a model and describing the shapes of its elements. Thus, all these five activities are important in tactile exploration.

Sensing

Sensing the shape and texture of a model was the most common activity participants performed when exploring the models. Most

Figure 2. Three printed models used in the study. From left to right: the Cell model, the Globe model, and the Map model.

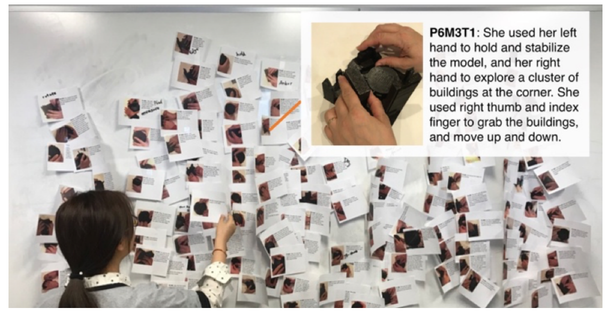

Figure 3. A researcher was clustering the note cards. Another participating researcher took the photo.

of the time participants moved their fingertips back and forth against the model to sense its texture; they occasionally used their palms and fingernails as well. To feel the shape of a model, they performed static gestures like holding the model firmly in their hands.

Measuring

Five participants used their hands to approximately measure the sizes of components on the models. Participants measured components on the Map model most, feeling the heights and widths of the rectangular buildings and the radius of the round building using proprioception. Participants performed these "measuring" activities during all tasks and for all models.

Comparing

Four participants mentioned they compared the shapes of two elements to confirm whether they represented the same concept. For example, P8 and P11 touched two semi-spheres on the Cell model to check whether they both represented Peroxisomes.

Counting

When a specific shape appeared more than twice, many participants counted the instances of the shape. We noted a counting activity whenever a participant verbally counted similar shapes, and found seven participants performed counting activities when exploring the Cell and Map models across three tasks. On the Cell model, participants counted the holes in the Nucleus. On the Map model, they counted the buildings and components of the buildings (e.g., the entrances of the round building).

Communicating

Eight participants communicated with the researchers during the three tasks. Their communication generally served three purposes:

- *Indication*: They used different gestures to tell the researchers that they found the specified element in Task 2.
- *Explanation*: They described their behavior and pointed out certain elements to the researchers.
- *Inquiry*: They asked questions about the identities of elements during the three tasks.

4.2 Hand Postures

Identified Postures

Participants held and manipulated the models using four distinct postures. Sometimes they only used one hand to explore the model, leaving the other hand to hold or stabilize the model. In other cases, they used both hands to explore the model. As shown in Figure 4, we identified four postures: *Grabbing, Stabilizing, Diverging, and Converging*. We described the four postures and their advantages in Table 1. All participants used the four postures throughout the exploration tasks except for P12, who only used the Grabbing posture.

Patterns of Hand Postures

We found participants actively and unconsciously switched among postures to explore the models. The posture a participant adopted depended on (1) the shape of the model being explored, (2) the size of the area the participant was perceiving, and (3) the exploration activity performed.

The shape of a model afforded the postures participants used to explore it. For example, ten participants only used the Grabbing posture when exploring the Globe model. P5 reflected on his posture and said, "I think it's easier with my hands [to hold the Globe model in the air]." While P6 thought she didn't use the Grabbing posture on the Map model because "I don't feel comfortable holding it." On the other hand, participants were more likely to put stable models (e.g., the Cell and the Map models) on the table and adopt the Stabilizing, the Diverging, and the Converging postures. P1 said he put the Map model on the table because "it has a solid base." P7 said she would have put the Globe model on the table if it had "the shape of a teardrop."

The size of the area participants explored also influenced their hand postures. For example, participants tended to use the Diverging posture when exploring large elements (e.g., the Golgi Apparatuses on the Cell model).

Postures also varied depending on what exploration activity the participant was performing. For example, all comparison activities were associated with the Diverging posture, with which participants could examine two elements at a same time.

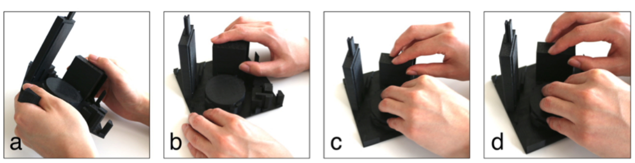

Figure 4. The four identified hand postures. From left to right: Grabbing, Stabilizing, Diverging, and Converging.

Meanwhile, in all communication activities participants used the Grabbing and the Stabilizing postures. Participants used one hand to grab or stabilize the models while using the other hand to point out elements to the researchers.

4.3 Gestures

Identified Gestures

We found eight gestures in the study. We classified a gesture by which parts of the hands were involved and whether it was static or dynamic. We define a *static gesture* as a gesture in which a participant pauses in the middle of performing an action with her hand. By contrast, we define a *dynamic gesture* as a gesture in which a participant performs an action that involves continuous movement. Static gestures were associated with cutaneous perception, while dynamic gestures involved haptic perception as well. In the study, participants performed four single-finger gestures (*i.e.*, *Pointing*, *Striking*, *Index Scanning*, and *Thumb Scanning*, as shown in Figure 5) and four multi-finger gestures (*i.e.*, *Pinching*, *Hovering*, *Following*, and *Rubbing*, as shown in Figure 6). The Pointing, Pinching, and Hovering gestures were static gestures, while the others were dynamic. We described the gestures in Table 2.

Patterns of Gestures

Participants unconsciously chose gestures based on (1) the ongoing activities and (2) properties of the areas they were exploring.

Participants used different gestures for different exploration activities. Table 3 shows the Gesture-Activity matrix, where we marked all combinations that appeared in the study. While the Rub gesture was more capable and could support all five activities, the other gestures served fewer activities. Three gestures only served a single type of activity.

The Pointing and the Striking gestures were only used when participants communicated with the researchers. Participants only used the Thumb Scanning gesture to sense the texture and shapes of elements of a model.

In addition to the influence of the activities, participants also chose gestures based on the complexity and the sizes of the areas they were exploring. When a model was simpler, they tended to use fewer fingers with gestures like Index Scanning, Thumb Scanning, and Hovering. P2 said, "If it's a larger, general model, I would use even the palms of my hands… I want to get everything at once, when I want to be specific, I will revert to my pointers." Other participants also shared similar thoughts. This is because fingers, especially fingertips, have a greater density of receptors, and are more sensitive to detailed tactile information [12]. On the other hand, the palms have larger contact surfaces and can sense larger elements or an entire model at the same time.

	Posture	Description	Advantages
Exploring Using One Hand	Grabbing	Use one hand to hold the model in the air, and perceive tactile information from the other hand.	Allowing a participant to use one hand to navigate and rotate the model freely.
	Stabilizing	Use one hand to fix a model on the table, and the other hand to learn the model.	Not only enabling a participant to explore the model stably, but also providing a reference point from his fixed hand.
Exploring Using Two Hands	Diverging	Put two hands on two elements separately, and each hand could perform different gestures.	Enabling a participant to explore two elements at the same time.
	Converging	Use both hands to explore a single element.	Allowing a participant to explore large elements (e.g., the Golgi Apparatuses in the Cell model) using both hands.

Table 1. The four identified hand postures.

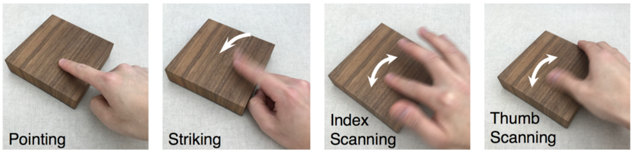

Figure 5. The four identified single-finger gestures. The movements of dynamic gestures are marked with arrows.

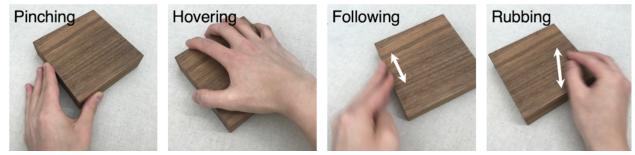

Figure 6. The four identified multi-finger gestures. The movements of dynamic gestures are marked with arrows.

	Posture	Description	Movement	Parts of Hands
Single-finger Gestures	Pointing	Hold an index finger on a model. Five participants used this Pointing gesture.	Static	Index fingers
	Striking	Strike a point on a model with quick light blows. Six participants performed this gesture.	Dynamic	Index fingers
	Index Scanning	Use index fingers to scan an area. Nine participants did this gesture.	Dynamic	Index fingers
	Thumb Scanning	Use thumbs to scan an area. Four participants did this gesture.	Dynamic	Thumbs
Multi-finger Gestures	Pinching	Grip a model using thumb, index, and middle fingers, and hold this gesture for a while to perceive tactile information. Five participants did this gesture.	Static	Thumbs, index, and middle fingers mainly
	Hovering	Put an entire hand on a model without observable movement. Eight participants used this gesture.	Static	Fingertips, palms, and finger pads
	Following	Use more than two fingers together to follow the edge of an element. Ten participants used this gesture.	Dynamic	Fingertips and finger pads
	Rubbing	Use nails, fingertips and finger pads to move around an area. All participants used this gesture.	Dynamic	Nails, fingertips and finger pads

Table 2. The eight gestures identified in the Exploration section.

	Sensing	Measuring	Comparing	Counting	Communicating
Pointing					X
Striking					X
Index Scanning	X	X	X	X	
Thumb Scanning	X				
Pinching	X	X			
Hovering	X	X		X	
Following	X				X
Rubbing	X	X	X	X	X

Table 3. The Gesture-Activity matrix. We marked all the combinations of exploration activities and gestures that appeared in the Exploration section of the study.

5. FINDINGS: ELICITATION

Ten of the 12 participants designed input techniques for all referents. Most used the same input techniques for referents across the three models. P5 thought recording notes and retrieving notes were unnecessary, and P12 thought selecting an area was not a reasonable referent. We report the input techniques participants proposed and summarized patterns from their designs.

5.1 User-Defined Input Modalities

In total, participants proposed 82 interactions for six referents, 58 of which were distinct on a per-referent basis. The suggested interactions covered three input modalities: gestures, speech input, and buttons. In Table 4, we divided the interactions into three modalities. Among all user-defined interactions, gestures were the most common modality and had the biggest variations.

	Total Techniques	Distinct Techniques
Gestures	56 (68.3%)	40 (70.0%)
Speech Input	13 (15.9%)	9 (15.5%)
Buttons	13 (15.9%))	9 (15.5%)
Total	82	58

Table 4. The total and distinct Techniques broken down by different interaction modalities.

Gestures

All participants except for P12 wanted to perform gestures on the models to trigger some referents. Some gestures they mentioned are commonly available on touchscreens or supported by screen reader software, such as tapping, touching, pressing with force, holding for a while and swiping. Some gestures had variations. For example, participants brought up different tapping gestures like a single-finger single tap, a two-finger single tap, and a two-finger triple tap. Participants sometimes combined two gestures to create a new gesture (e.g., a tapping gesture followed by a press gesture).

Several participants designed gestures that were not based on current eyes-free touchscreen interaction. P2 wanted to shake a model to get general information about it, and squeeze an element to get its name. P10 used her fingers to follow the edge of an area, which we defined as the Following gesture (see above), to select it. P9 scratched an area to select it.

Two participants described principles that guided their proposed gestures. P6 used speed as a parameter to trigger different referents. For example, a user could perform a swiping gesture quickly on an element to get general information about it, and then slow down to retrieve more detailed information. P8 introduced the Rochester Method [28], also known as Visible English. He drew a symbol representing a question mark (as defined by the Rochester Method) to retrieve general information about a model.

Speech Input
Five participants mentioned speech input. They used simple commands such as "what is it?" "more information," and "save information." P11 said these commands were inspired by Siri on the iPhone.

Buttons
Participants designed buttons to fulfill different functions, and arranged them in different locations. For example, P5, P7, P12 wanted to have a button that could turn on the audio feedback of an I3M, and speak general information about the model. P3 designed buttons to get detailed information and take notes. However, three participants emphasized that the buttons should not be incorporated into the models. P7 commented on the effect of buttons on the tactile information represented on a model, saying that "adding buttons to the structure almost takes away from actually teaching someone what is the thing you are touching." They suggested placing the buttons at the bottom of a model or on an auxiliary component like the long stick we added.

5.2 Elicited Interactions for Referents

On average, each referent got 13.7 input techniques, and 9.7 distinct input techniques. When broken down into the three input modalities (gestures, speech, and buttons), there were 6.7 distinct gestures, 1.5 distinct speech input commands, and 1.5 distinct button arrangements per referent.

To further understand user agreement of proposed interactions for each referent, we calculated the max-consensus (MC) and consensus-distinct ratio (CDR). MC is the percent of participants who suggested the most popular input technique for a referent or referent/input modality combination. A higher MC value indicates more user agreement on the most popular user-defined input technique. For a referent or referent/interaction technique combination, CDR is the percent of the distinct techniques that achieved a given consensus threshold among participants. This metric indicates the diversity of techniques that fulfill a certain user agreement. We used a threshold of two in the analysis.

In Table 5, we list MC, CDR, and the distinct input techniques that were above the consensus threshold for each referent. Across all referents, gestures received more user agreement with a mean MC of 20.8%, compared to speech input (mean MC = 11.1%) and buttons (mean MC = 12.5%). However, speech input and buttons were more favored for referents that do not involve specific model elements. For example, the referent "Get General Model Information" had a MC of 25% for buttons, but a MC of 17% for gestures. The referent "Get More Information" had a MC of 25% for speech input, compared to a MC of 17% for gestures. P3, who designed a button for "Get General Model Information," said that "it doesn't matter if you are feeling it (the model)."

For each referent, we can choose the technique with the highest number of the supporting participants (i.e., the first action in each row) as its elicited interaction. In this study, our elicited interaction set is conflict-free. Prior work [42] introduced a method to eliminate conflicts in elicited interactions.

6. DESIGNING I3MS

We conclude design implications for I3Ms from the study, and propose a set of recommended interactions and functions.

6.1 Design Implications

We draw design implications from both sections of the study. These implications can be used as design guidelines for future I3Ms.

Improving Tactile Information
I3Ms are augmented 3D printed objects. Thus, we need to consider the printed model itself when design an I3M. The findings from the study imply that designers should make tactile information clearer, and consider potential technology failures in 3D prints.

We could design different versions of a model to meet the needs of users with varied tactile perception abilities and avoid overwhelming information. Participants said that some models contained an overwhelming amount of details. For example, when exploring the Globe model, P6 said, "In North America, there are so many details, and I can't distinguish what they are and what they mean." Another participant, P12, thought the raised edges on the Globe model were unnecessary and confusing, and suggested that we produce different models to meet the needs of people with varied educational backgrounds. For example, when designing a model for a continent, we could have a detailed version where

Referent	MC/CDR Type	MC	CDR	Above Threshold Distinct input actions	#
Get General Model Information	Overall	25%	23%	• Push a button on the long stick to turn on the model	3
	Gestures	17%	22%	• Use index finger to press the model at beginning	2
	Speech	8%	0%	• Use index finger to touch the model at beginning	2
	Buttons	25%	50%		
Select an Element and Get its Name	Overall	25%	40%	• Use index finger to tap once on the element	3
	Gestures	25%	44%	• Use index finger to press the element	3
	Speech	-	-	• Use index finger to touch the element	2
	Buttons	8%	0%	• Use index finger to tap twice on the element	2
Select a Sub-Area of an Element and Get its Name	Overall	33%	29%	• Use index finger to swipe on the area	4
	Gestures	33%	17%	• Push a button on the long stick to switch the level of information	2
	Speech	-	-		
	Buttons	17%	100%		
Get More Information	Overall	25%	40%	• "more information"	3
				• Use index finger to swipe on the element/area	2
	Gestures	17%	38%	• Use index finger to tap twice on the element/area	2
	Speech	25%	100%	• Use index finger to tap on the element/area and hold	2
	Buttons	8%	0%		
Record Notes	Overall	17%	22%	• "record notes"	2
	Gestures	17%	20%		
	Speech	17%	50%	• Use index finger to tap on the element/area twice	2
	Buttons	8%	0%		
Retrieve notes	Overall	17%	22%	• "retrieve notes"	2
	Gestures	17%	20%		
	Speech	17%	50%	• Use index finger to tap on the element/area twice	2
	Buttons	8%	0%		

Table 5. Six referents and their max-consensus (MC) values, consensus-distinct ratios (CDRs), and distinct input actions that were above a consensus threshold of two. The MC and CDRs were also broken down into three input modalities. Two referents didn't get any speech interaction. For each distinct input action, we list the number of the participants reporting in the "#" column.

major cities are marked. In addition, we could create a simplified version that only has general geographic information. Since 3D printers produce low-cost models in a relatively short time, blind users can print and experience different versions of a model to meet their needs. Moreover, recent research on 3D printers allows us to modify an existing model [39]. Using similar tools, a blind user can learn from a simplified version and ask a printer to add more details when she gets a better understanding of the model.

To overcome potential technology failures, we propose using specific tactile patterns to avoid imperfections, and using software solutions to optimize 3D prints. For example, designers could mark each element on a globe model with different tactile patterns. In this way, users will understand which part belongs to an element and they could learn to ignore printing imperfections. In addition, designers can use software applications like MeshMixer [2] that increase the durability and printing quality of models.

Controllable and Changeable Digital Content

In the Elicitation section, four participants specifically point out the potential issue of overwhelming audio feedback. They worried that the models would keep providing unnecessary audio output when they were exploring the models. P5 said, "It's annoying, if you are feeling, it keeps saying nucleus, nucleus, nucleus, every time you touch it, that would be irritating." P7 further explained the reason behind this, "People don't take a ton of information well, instead, it overwhelms them. So, they need to be very much in control of the information they are accessing."

We propose to use modes to change content and avoid overwhelming the user with information. In the study, four participants said they would like to be able to switch among different modes using a switch or a button. The most basic modes they mentioned were turning on and turning off the audio output. In addition, the embedded audio content of an I3M could be customized to meet varied needs from different users. P3 and P5 also thought the models could have modes with different levels of information. For example, P3 mentioned "national mode," "state mode," and "city mode" for the Globe model. In addition, P4 thought these models could also serve different purposes. He designed two settings as an example, "One setting is to give general information, or element information. Another setting is to allow people to guess [the name of an element]."

Supporting Exploration Behaviors

I3Ms should contain adequate information to support the exploration activities blind people perform when perceiving a model. Prior work [9, 17, 25, 30–32, 38] only provided simple label information for each element on a 3D model. However, in the Exploration section, blind people also showed their interest in the dimensions of elements, similarities among elements, and the number of repeated elements.

We also need to consider blind people's exploration behaviors when designing auxiliary components for I3Ms. I3Ms rely on additional sensors to sense users' behaviors. Some auxiliary components require a fixed model, and might not be suitable for models without a stable base. For example, prior work [9, 17, 38] used conductive filament and touchscreens to create I3Ms, which required users to attach the model onto a tablet when use it. This method could fail in the case of a model that does not have a stable base (e.g., the Globe model), because blind people tended to hold that model in the air and use the Grabbing posture to explore it. When designed in a suitable form, an auxiliary component could help tactile exploration. For example, P3 used the long stick as a handle so she could hold models steadily, as shown in Figure 7.

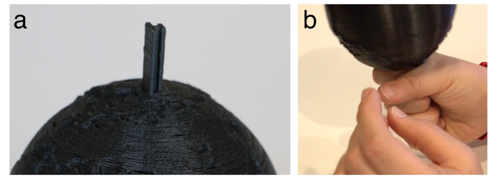

Figure 7. Participants took advantage of (a) the long stick we added on each model. For example, (b) P3 used it as a handle to stabilize and manipulate the model.

Learnable and Distinguishable Gestures

When using gestures as the main input modality for I3Ms, we should consider the learnability of the gestures, as well as how to distinguish the gestures from regular exploration behaviors.

On the one hand, we should use common gestures to lower the learning curve of interactive models. In the Elicitation section of our study, the participants designed common touchscreen gestures. P7 attributed her reasons for doing this to the learnability of gestures, and said "every time you do something, there is a learning curve," a thought shared by other participants as well. In addition to the gestures from the Elicitation section, we also identified some learnable gestures in the Exploration section. For example, the Pointing, Striking, and Following gestures are used in communication activities to inquire information. These gestures are intuitive ways to communicate with I3Ms.

On the other hand, I3Ms should also be able to distinguish deliberate gestures from exploration behaviors. Some participants also expressed their concerns about gesture recognition. When designing gestures, a designer should consider the exploration behaviors we highlighted and avoid potential confusion.

Interaction Techniques for Small Models

Three participants felt that the small size of the models limited the design space for gestures. When designing input techniques for the Globe model, P3 said, "If you want multiple state information, it would be hard to do in an item that's small."

Since current mainstream printers could only produce models with a limited size, we should combine different interaction techniques to overcome this constraint. For example, while selecting a state in the Globe model was difficult, the participants chose other methods like speech input to retrieve information.

6.2 Proposed Design

Our proposed design uses an RGB camera, a microphone, and a touchscreen from a tablet as sensors, and is an extension of our ongoing work [31, 33]. With these sensors, a user can use gestures, speech input, and physical and virtual buttons to interface with an I3M, as shown in Figure 8. We describe the functions and interactions of the proposed design in Table 6.

The findings from both sections of the study contributed to our proposed design. The exploration behaviors we identified implied the potential functions blind people need. For example, the proposed design enables them to compare elements or areas and inquiry the dimension information of an element. The elicited input techniques yielded insights about blind participants' preferences for different interaction techniques, as well as their opinions about I3Ms. For instance, we design virtual and physical buttons that enable users to control information flow. The I3Ms we design have two modes: "Element" and "Area." For example, on a globe model, users can perform inquiries about continents in the "Element" mode, and the "Area" mode provides information about countries.

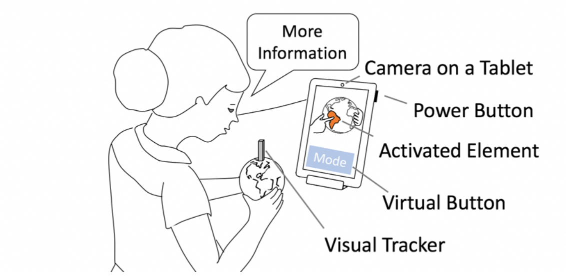

Figure 8. A use case for the proposed design. A user selects an element with her index finger, and says “more information” to retrieve further information about the element.

Functions	Interactions
Turn on/off	Power button
Switch modes	Virtual button
Select a Sub-Area of an Element and Get its Name	Use index finger to tap once on the element/area
Compare two elements/areas	“Comparison” + Use index finger to tap once on two elements/areas
Get dimension	“Dimension” after selecting
Get more information	“More information” after selecting

Table 6. The functions and interactions for the proposed design.

7. DISCUSSION

We conducted a study with blind participants and discussed design implications for I3Ms. In addition to I3Ms, the findings from our study can also contribute to the design of passive printed models. Passive printed models also faced challenges in terms of design and technology, as we described in Section 6.1. Thus, model designers should consider our guidelines to improve tactile information for passive printed models. Moreover, designers should provide accessible information (e.g., tactile Braille prints, audio books) to explain the information included in the models to avoid confusion, if that information isn’t accessible interactively.

In the Exploration section of our study, we developed a new taxonomy to analyze exploration behaviors. We classified each note card in three dimensions: exploration activities, hand postures, and gestures. We defined hand postures based on the functionalities of hands, and specified each gesture by its movement and which parts of the hands it involved. With this taxonomy, we coded all note cards. While prior work on tactile perception [19] and elicitation [23, 42] introduced several taxonomies that might yield other perspectives, we believe our inductive approach captured a range of salient behaviors in the relatively unexplored space of the perception of 3D models.

In the Elicitation section of our study, we asked participants to design input techniques to retrieve audio information about models and their components. We used audio as the default output since all prior work on I3Ms provided audio feedback. However, other output modalities, such as smells and vibrations, can also be applied to I3Ms [4]. Visual feedback can also be important for people with low vision, who comprise the majority of the population of people with visual impairments [36, 37]. We plan to conduct further studies to explore potential output techniques.

We proposed a design of I3Ms using the sensors in a tablet. The sensors a designer chooses will affect the design of I3Ms. For example, RGB cameras are ubiquitous, but they are less capable of differentiating touching and pressing gestures. Moreover, sensors can also affect the design of auxiliary components. In the study, we added a long stick on each model to represent an auxiliary component. We found that such components wouldn’t bother users if they were designed to support users’ exploration behaviors. Model designers should choose sensors based on use cases, and adopt the findings from this study.

The proposed design enables a blind user to retrieve information from I3Ms, but we think I3Ms themselves could take more initiative and guide users through the exploration process of a model. Prior work [22] suggested that by following some exploration patterns, blind users could learn tactile information more efficiently. I3Ms should be able to help users find the best strategy to explore models. However, we need further research to design accessible and efficient instructions to guide this process.

The findings of our study could be more substantial with future research. The identified exploration behaviors should be confirmed with more participants, and the design implications we concluded should be further examined. Moreover, the proposed design should be validated in an iterative design process.

8. CONCLUSIONS

In this paper, we conducted a study with 12 legally blind participants to understand blind people’s exploration behavior with 3D printed models and elicit interactions for future I3Ms. With the design implications concluded from the study, we proposed a design of I3Ms. The findings in the study lay an important foundation for future research and design of I3Ms which could serve as powerful accessibility tools.

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